Review

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Enabling the environmentally clean air transportation of the future: a vision of computational fluid dynamics in 2030

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As global air travel expands rapidly to meet demand generated by economic growth, it is essential to continue to improve the efficiency of air transportation to reduce its carbon emissions and address concerns about climate change. Future transports must be 'cleaner' and designed to include technologies that will continue to lower engine emissions and reduce community noise. The use of computational fluid dynamics (CFD) will be critical to enable the design of these new concepts. In general, the ability to simulate aerodynamic and reactive flows using CFD has progressed rapidly during the past several decades and has fundamentally changed the aerospace design process. Advanced simulation capabilities not only enable reductions

in ground-based and flight-testing requirements, but also provide added physical insight, and enable superior designs at reduced cost and risk. In spite of considerable success, reliable use of CFD has remained confined to a small region of the operating envelope due, in part, to the inability of current methods to reliably predict turbulent, separated flows. Fortunately, the advent of much more powerful computing platforms provides an opportunity to overcome a number of these challenges. This paper summarizes the findings and recommendations from a recent NASA-funded study that provides a vision for CFD in the year 2030, including an assessment of critical technology gaps and needed development, and identifies the key CFD technology advancements that will enable the design and development of much cleaner aircraft in the future.

1. Introduction

Commercial aviation is a critical component of the global economic infrastructure, and accounts for between 2 and 3% of anthropogenic greenhouse gas emissions. A recent report [1] co-authored by the US Department of Transportation forecasts global CO₂ emissions of 1.5 billion tons per year by 2025 due to commercial aviation, roughly the same amount as predicted by the International Panel on Climate Change in 1999 for the same year (IPCC, <http://www.ipcc.ch/>). While the aviation industry has continued to develop technologies and introduce airplanes with improved efficiency, the historic rates of efficiency gains are inadequate to reduce the overall growth in CO₂ emissions, as illustrated in that report. In addition to climate change, the report suggests that the number of people exposed to significant objectionable aircraft noise will increase, despite the ongoing introduction of quieter next-generation jet engines and airplanes. Commercial aviation is already an industry economically driven by fuel efficiency; the aviation industry has recognized these challenges and has made aggressive commitments to reduce its environmental footprint, with a key goal of achieving carbon neutral growth by 2020 and a 50% net reduction of CO₂ emissions by 2050 relative to 2005. The strategy for achieving these goals includes continued development of airplane technology for improved airplane efficiency, increased operational efficiency of those aircraft through improved airline operations and airspace infrastructure, and the commercialization of drop-in sustainable aviation fuels.

To address the airplane technology pillar of this strategy, various advanced-technology alternatives are envisioned to improve the environmental performance of commercial aviation in the 2030–2040 timeframe [2]. Aside from lower life cycle carbon emission fuels for the primary propulsion systems, the most credible approaches to significant CO₂ reductions will require radical changes to the configuration of the aircraft [3], its propulsion system [4] and structural design. Several advanced configurations are being proposed, such as hybrid-wing body aircraft, vehicles with extremely large spans and truss- or strut-braced wings, joined wing concepts and others. In addition, a revolution in the performance of future jet engines (e.g. ultra-high bypass ratio engines, geared turbofans, open rotors, advanced combustors, etc.) is underway with nearly half of the overall fuel efficiency improvement estimated to come from the propulsion system. Coupled with advanced aero-structural concepts such as load alleviation and morphing and control methods to manage the inherent flexibility resulting from high span and very low weight, the improvements can be substantial and would help realize (with the introduction of sustainable alternative jet fuels) the ambitious targets that the community has set for itself in 2050 [5].

Currently, it is challenging to efficiently design the new aircraft, jet engines and propulsion systems that are required to meet these ambitious fuel efficiency, emissions and noise targets [2] without large uncertainties. Specifically, the analysis and design tools available lack the necessary predictive capabilities and the validation database to confidently move forward. As a result, these shortcomings in our analysis capabilities increase the risk incurred in the development of future vehicles and engines. In particular, many of the future technology advancements mentioned above will depend heavily on our ability to compute fluid flows in a variety of situations

including attached and separated flows, high-lift systems, three-dimensional turbomachinery, high-speed flows, combustion, aeroacoustics, aircraft noise shielding and so forth. Without sizable improvements in our computational fluid dynamics (CFD) and other simulation capabilities, and the integration of these improvements into the design process, the ability to tackle the challenges of environmentally clean air transportation will be significantly limited.

For this reason, a team of government, industry, and academic researchers and engineers came together to assess the current state of CFD methods and create a technology development plan to achieve revolutionary advances in CFD capability in the notional 2030 timeframe. The Vision 2030 CFD study [6], commissioned by NASA, addresses the critical CFD technologies needed to enable future environmentally responsible aviation. The remainder of this article summarizes the major results from the study of relevance to the CFD community and borrows heavily from the text contained in the final contractual report.

2. Vision 2030 computational fluid dynamics study

The objective of the Vision 2030 CFD study was to develop a knowledge-based forecast and research strategy for a visionary CFD capability in 2030. Inputs from a team of subject matter experts in aerodynamics, aerospace engineering, applied mathematics and computer science were used to define an initial vision and research plan. Additional refinement of the vision and research plan was obtained from the broader CFD technical community through the development and execution of an online survey, and through a technical workshop with participants from the general aerospace engineering community with a stake in simulation-based engineering. The results from the survey and workshop were synthesized and refined by the team, with considerable additions through internal discussions and feedback from sponsoring NASA officials.

The first outcome of the study consists of a set of findings that, in essence, summarizes the impediments in the current state of the field that must be overcome to enable the superior simulation capabilities required for the challenges of clean aviation. After briefly describing these key findings, a vision of the required capabilities for CFD in the notional year 2030 is formulated. By contrasting this vision with the current state of the field, important areas of required investment are identified and assembled in a logical fashion into six broad technical areas that constitute the core elements of a proposed long-term research programme. Additionally, a set of grand challenge (GC) problems are devised and used as application drivers to assess progress towards the long-term research objectives, and to identify and prioritize the various areas of investment. The paper concludes with a set of recommendations for the community at large in terms of strategy and future investments required for meeting the simulation challenge for clean aviation in the twenty-first century.

(a) Key findings

- (1) Investment in basic research and technology development for simulation-based analysis and design has declined significantly in the past decade, and must be reinvigorated if substantial advances in simulation capability are to be achieved. Advancing simulation capabilities will be critically important for enabling environmentally sustainable aviation in the twenty-first century. Furthermore, advances in foundational technologies, as well as increased investment in software development will be required, since problem and software complexities continue to increase exponentially.
- (2) High-performance computing (HPC) hardware is progressing rapidly and technologies that will prevail are difficult to predict. However, there is a general consensus that HPC hardware is on the cusp of a paradigm shift that will require significantly new algorithms and software in order to exploit emerging hardware capabilities. While the dominant trend is towards increased parallelism and heterogeneous architectures, alternative new

technologies offer the potential for radical advances in computational capabilities, but these are still in their infancy.

- (3) The use of CFD in the aerospace design process is severely limited by the inability to accurately and reliably predict turbulent flows with significant regions of separation. Advances in Reynolds-averaged Navier–Stokes (RANS) modelling alone are unlikely to overcome this deficiency, while the use of large-eddy simulation (LES) methods will remain impractical for various important applications for the foreseeable future, barring any radical advances in algorithmic technology. Hybrid RANS/LES and wall-modelled LES offer the best prospects for overcoming this obstacle although significant modelling issues remain to be addressed. Furthermore, other physical models such as transition and combustion will remain as pacing items.
- (4) Mesh generation and adaptivity continue to be significant bottlenecks in the CFD workflow. As more capable HPC hardware enables higher resolution simulations, fast, reliable mesh generation and adaptivity will become more problematic. Additionally, adaptive mesh techniques offer great potential, but have not seen widespread use due to issues related to software complexity, inadequate error estimation capabilities and complex geometries.
- (5) Revolutionary algorithmic improvements will be required to enable future advances in simulation capability. Traditionally, developments in improved discretizations, solvers and other techniques have been as important as advances in computer hardware in the development of more capable CFD simulation tools. However, the lack of investment in these areas and the supporting disciplines of applied mathematics and computer science have resulted in stagnant simulation capabilities. Future algorithmic developments will be essential for enabling much higher resolution simulations through improved accuracy and efficiency, for exploiting rapidly evolving HPC hardware, and for enabling necessary future error estimation, sensitivity analysis and uncertainty quantification techniques.
- (6) Managing the vast amounts of data generated by current and future large-scale simulations will continue to be problematic and will become increasingly complex due to changing HPC hardware. These include effective, intuitive and interactive visualization of high-resolution simulations, real-time analysis, management of large databases generated by simulation ensembles and merging of variable fidelity simulation data from various sources, including experimental data.
- (7) In order to enable increasingly multidisciplinary simulations, for both analysis and design optimization purposes, advances in individual component CFD solver robustness and automation will be required. The development of improved coupling at high fidelity for a variety of interacting disciplines will also be needed, as well as techniques for computing and coupling sensitivity information and propagating uncertainties. Standardization of disciplinary interfaces and the development of coupling frameworks will increase in importance with added simulation complexity.

(b) Vision

CFD in 2030 is grounded on a desired set of capabilities that must be present for a radical improvement in numerical predictions of critical flow phenomena associated with not only commercial aircraft and propulsion systems, but also with the key aerospace product/application categories, including military aircraft, rotorcraft, space exploration systems, launch vehicle programmes, air-breathing space-access configurations and spacecraft entry, descent and landing. The basic set of capabilities for Vision 2030 CFD must include, at a minimum:

- (1) Emphasis on physics-based, predictive modelling. In particular, transition, turbulence, separation, chemically reacting flows, radiation, heat transfer and constitutive models must reflect the underlying physics more closely than ever before.
- (2) Management of errors and uncertainties resulting from all possible sources: (i) physical modelling errors and uncertainties related to item no. 1, (ii) numerical errors arising

- from mesh and discretization inadequacies, and (iii) aleatory uncertainties derived from natural variability, as well as epistemic uncertainties due to the lack of knowledge in the parameters of a particular fluid flow problem.
- (3) A much higher degree of automation in all steps of the analysis process including geometry creation, mesh generation and adaptation, the creation of large databases of simulation results, the extraction and understanding of the vast amounts of information generated and the ability to computationally steer the process. Inherent to all these improvements is the requirement that every step of the solution chain executes at high levels of reliability/robustness to minimize user intervention.
 - (4) Ability to effectively use massively parallel, heterogeneous and fault-tolerant HPC architectures that will be available in the 2030 timeframe. For complex physical models with non-local interactions, the challenges of mapping the underlying algorithms onto computers with multiple memory hierarchies, latencies and bandwidths must be overcome.
 - (5) Flexibility to tackle capability- and capacity-computing tasks in both industrial and research environments so that both very large ensembles of reasonably sized solutions (such as those required to populate full-flight envelopes, operating maps or for parameter studies and design optimization) and small numbers of very large-scale solutions (such as those needed for experiments of discovery and understanding of flow physics) can be readily accomplished.
 - (6) Seamless integration with multidisciplinary analyses without sacrificing accuracy or numerical stability of the resulting coupled simulation, and without requiring a large amount of effort such that only a handful of coupled simulations are possible.

(c) Computational fluid dynamics development plan

To achieve the vision of CFD in 2030, sustained and focused investment in key technologies will be required. A set of six key technology areas has been identified that, when taken together, form the core of a comprehensive CFD development plan that should be considered by various national and international agencies with a stake in the future development of clean aviation.

(i) High-performance computing

Advances in HPC hardware systems and related computer software are critically important to the advancement of the state of the art in CFD simulation, particularly for high Reynolds number turbulent flow simulations. HPC technology will probably advance along two separate paths. Ongoing development of exascale systems will continue through 2030 and represents the technology that will most probably provide the large increase in throughput for CFD simulation during this timeframe (<http://www.exascale.org>) [7]. However, novel technologies, such as quantum computing or molecular computing, offer a true paradigm shift in computing potential and must be carefully considered at strategic points in the overall development plan, even though the technology is at a very low maturity level today.

In considering the likely performance of HPC systems in the future, it is important to recognize that the same rate of performance improvement that has been maintained over the past several decades is unlikely to continue. Already, clock rates of the individual processing elements have remained nearly constant since 2007. The rate at which individual features shrink on an integrated circuit has also slowed significantly. In this sense, Moore's law, which is really an observation (and has been an engineering goal) about the rate at which feature sizes shrink, is already breaking down. Other issues, such as power consumption and heat dissipation, are limiting the performance of processors. To compensate for these issues, computer architects have been rapidly increasing the amount of parallelism and developing optimized but less general-purpose architectures. The largest current systems already have over one million cores and many use a combination of general-purpose CPUs and graphics processing units, which are optimized for stream computing. These issues lead to several observations: (i) a sustained exaFLOP (10^{18}

operations per second on a CFD application) may not be achieved until 2020 or later, (ii) HPC systems in 2020–2030 will be characterized by heterogeneous hardware nodes, containing several types of specialized processing elements and deep memory hierarchies, and (iii) extreme degrees of parallelism, of at least a billion-way for an exaFLOP system, will be common. Current predictions are that a 30 exaFLOP system should be possible in 2030. Innovation in hardware is likely to change the details of the system (e.g. specialized processing elements and multilevel memory hierarchies) but not the general nature of the system. These systems, while able to run current algorithms and code, will not do so efficiently.

In order to properly address the HPC challenge, three specific thrusts must be considered. First, current simulation software must be ported in evolving and emerging HPC architectures with a view towards efficiency and software maintainability. Second, investments must be made in the development of new algorithms, discretizations and solvers that are well suited for the massive levels of parallelism and deep memory architectures anticipated in future HPC hardware [8,9]. Finally, increased access to the latest large-scale computer hardware must be provided and maintained, not only for production runs, but also for algorithmic research and software development projects, which will be critical for the design and validation of new simulation tools and techniques [10,11].

(ii) Physical modelling

Advances in the physical modelling of turbulence for separated flows, transition and combustion are critically needed to achieve the desired state of CFD in 2030 [8,12–17]. For the advancement of turbulent flow simulation, three separate tracks for research are proposed: RANS-based turbulence treatments; hybrid RANS/LES approaches where the entire boundary layer is resolved with RANS-based models, and the outer flow is resolved with LES models; and LES, including both wall-modelled (WMLES) and wall-resolved (WRLES).

RANS-based turbulence models continue to be the standard approach used to predict a wide range of flows for very complex configurations across virtually all aerospace product categories [13,18–21]. They are easy to use, computationally efficient and generally able to capture wall-bounded flows, flows with shear, flows with streamline curvature and rotation and flows with mild separation. For these reasons, as well as the fact that RANS models will remain as an important component in hybrid RANS/LES methods, their use will continue through 2030. An advanced formulation of the RANS-based approach, where the eddy viscosity formulation is replaced with the direct modelling of the Reynolds stresses, known as the Reynolds stress transport (RST) method [22], will in principle be able to capture the onset and extent of flow separation for a wider range of flows [23]. Continued investment in RST models is envisioned into the 2020 timeframe, including careful implementation, verification and validation of the most promising variants of these models into research and production CFD codes.

Hybrid RANS/LES methods show perhaps the most promise in being able to capture more of the relevant flow physics for complex geometries at an increasingly reasonable computational cost [24,25]. However, although hybrid methods are making their way into current design practice, several issues still exist. First, the prediction of any separation that is initiated in the boundary layer will still require improvements in RANS-based methods. Second, a seamless, automatic RANS-to-LES transition in the boundary layer is needed to enhance the robustness of these methods. Continued investment in hybrid RANS/LES methods to specifically address these two critical shortcomings will be required. Additionally, more effective discretizations and solvers designed specifically for LES-type problems must be sought. When combined with advances in HPC hardware, these three developments will enable continued reduction in the RANS region as larger resolved LES regions become more feasible.

Application of LES to increasingly complex flows is a very active research area [26]. Cost estimates of WRLES show scaling with Reynolds number of about $Re_L^{2.5}$ while WMLES is about $Re_L^{1.3}$, with the costs being the same at Re_L of approximately 10^5 . For the typically higher Reynolds numbers and aspect ratios of interest to external aerodynamics, WRLES will be outside of a

24 h turnaround period even on 2030 HPC environments unless substantial advances are made in numerical algorithms. However, WRLES is potentially feasible in 2030 for lower Reynolds numbers and is a reasonable pursuit for many relevant aerospace applications, including many components of typical aerospace turbomachinery [27]. WMLES requires additional development of the wall-modelling capability [28]. As such, investments in LES research are needed with emphasis on (i) improved utilization of HPC including developments of numerical algorithms that can more effectively use future HPC environments and (ii) improved wall-modelling capability necessary for reliable WMLES.

Transition modelling is also a key area of investment, as an effective transition model would benefit RANS, hybrid RANS/LES and LES (by relieving mesh requirements in the laminar and transition regions). Thus, reliable and practical transition models must be developed and incorporated in the turbulence models being matured. The transition prediction method should be fully automatic, and be able to account for transition occurring from various mechanisms such as Tollmien–Schlichting waves, cross-flow instabilities, Görtler vortices and nonlinear interactions associated with bypass transition.

In the area of turbulent reactive flows, the development of a validated, predictive, multiscale combustion modelling capability to understand and optimize the performance of current and future fuels (including drop-in aviation alternative fuels) for advanced engines is needed. The principal challenges are posed by the small length and time scales of the chemical reactions (compared to turbulent scales), the many chemical species involved in hydrocarbon combustion, and the coupled process of reaction and molecular diffusion in a turbulent flow field. Current combustion modelling strategies rely on developing models for distinct combustion regimes, such as non-premixed, premixed at thin reaction zone and so forth. The predictive technology should be able to switch automatically from one regime to another, as these regimes coexist within practical devices. Furthermore, research should continue into methods to accelerate the calculation of chemical kinetics so that the CFD solution progression is not limited by these stiff ordinary differential equations.

Finally, investigation of radically novel approaches to physical modelling that may offer revolutionary changes in capabilities should be pursued. As an example, renormalization group theory [29,30] has been proposed as a general framework for turbulence and other multiscale physical modelling, although revolutionary advances have not materialized specifically for turbulence modelling. Nevertheless, advances in multiscale modelling such as systematic upscaling (SU) [31,32] offer the possibility for step changes in physical modelling capability and should be pursued in a measured manner.

(iii) Numerical algorithms

The development of novel numerical algorithms will be critical to achieving the stated CFD 2030 goals. Indeed, the proposed GC problems are sufficiently ambitious that advances in HPC hardware alone during the next 20 years will not be sufficient to achieve these goals. The focus of investment must be on discretizations and solvers that scale to massive levels of parallelism, that are well suited for the high-latency, deep memory hierarchies anticipated in future HPC hardware and that are robust and fault tolerant [9].

Discretization techniques such as higher order accurate methods offer the potential for better accuracy and scalability, although robustness and cost considerations remain [33]. Investment must focus on removing these barriers in order to unlock the superior asymptotic properties of these methods, while at the same time pursuing evolutionary improvements in other areas such as low dissipation schemes [34–36], flux functions and limiter formulations. Simultaneously, novel non-traditional approaches, such as lattice Boltzmann methods [37,38], should be investigated for special situations, particularly in low Mach number applications for complex configurations including computational aeroacoustics. Improved linear and nonlinear solvers must be developed, and here as well, the focus must be on highly scalable methods that are designed to be near optimal for the large-scale, time-implicit unsteady CFD and multidisciplinary

design and optimization (MDAO) simulations anticipated in the future. These may include the extension of well-known matrix-based techniques, Krylov methods [39], highly parallel multigrid methods [40] or the development of completely novel approaches such as SU methods [31,32]. For complex multiscale physical systems, where equations are solved based on first principles at the microscopic level, SU methods provide a rigorous computational framework and rules to process the system at increasingly larger, macroscopic scales. Investment in discretizations and solvers must also consider the potential of these methods to operate on dynamically adapting meshes, to enable optimization procedures and to incorporate advanced uncertainty quantification capabilities. Longer term, high-risk research should focus on the development of truly enabling technologies such as monotone or entropy stable schemes [41,42] in combination with innovative solvers on large-scale HPC hardware.

With regard to uncertainty quantification, large-scale probabilistic CFD for aerospace applications should be emphasized. Initially, activity in this area should focus on enabling current aerospace CFD tools with well-known uncertainty quantification techniques, such as sensitivity analysis and propagation methods using adjoints and forward linearizations, non-intrusive polynomial chaos methods and other reduced-order model formulations [43,44]. Additionally, a concerted effort should be made to characterize important aerospace uncertainties and to make these available to the general research community. Improved error estimation techniques must be investigated and developed, given the known deficiencies of current approaches (including adjoint methods). Finally, longer term research must focus on statistical approaches such as Bayesian techniques for quantifying more accurately modelling and other nonlinear error sources [45].

(iv) Geometry and grid generation

Substantial new investment in geometry and grid generation technology will be required in order to meet the Vision CFD 2030 goals. In general, this area remains one of the most important bottlenecks for large-scale complex simulations. Focused research programmes in streamlined CAD access and interfacing, large-scale mesh generation and automated optimal adaptive meshing techniques are required. Efforts must concentrate on making mesh generation and adaptation less burdensome and, ultimately, invisible to the CFD process, while developing technologies that enable the Vision 2030 CFD capabilities, namely very large-scale parallel mesh generation, curved mesh elements for higher order methods [46,47], highly scalable dynamic structured and unstructured overset mesh technology [48,49] and *in situ* anisotropic adaptive methods for time-dependent problems. Advances in these areas will require incremental software development, combined with advances in fundamental areas such as computational geometry. Additionally, because significant technology currently resides with commercial software vendors, particularly for CAD interfaces and access, involving these stakeholders in the appropriate focused research programmes will be critical for long-term success.

(v) Knowledge extraction

Petascale and exascale simulations will generate vast amounts of data. In order to make effective use of large-scale simulations in aerospace engineering, focused research in data knowledge extraction is required. Ideally, this should contain three components: visualization, database management and variable fidelity, data integration techniques.

Methods to process and visualize very large-scale unsteady CFD simulations in real time, including results from higher order discretizations, are required to support the advanced CFD capabilities envisioned in 2030. Although many of the current efforts in maturing visualization technology are being led by commercial vendors, more fundamental research to directly embed visualization capabilities into production CFD tools optimized for emerging HPC platforms is needed to achieve real-time processing [50]. Moreover, the CFD capability in 2030 must provide the analyst with a more intuitive and natural interface into the flow solution to better understand complex flow physics and data trends and enable revolutionary capabilities such as

computational steering, which could be used, as an example, for real-time virtual experiments or virtual flight simulation [51,52].

Foreseeing the capability of generating large databases with increasing computational power, techniques for rapidly integrating these databases, querying them in real time, and enhancing them on demand will be required, along with the ability to provide reliable error estimates or confidence levels throughout all regions of the database.

Finally, integrating high-fidelity simulation data with lower fidelity model data, as well as experimental data from wind tunnel tests, engine test rigs or flight-test data will provide a powerful approach for reducing overall risk in aerospace system design [53]. Techniques for building large-scale flexible databases are in their infancy, and range from simple software infrastructures that manage large numbers of simulation jobs to more sophisticated reduced-order models [54], surrogate models and Kriging methods [55,56]. The objective of research in this area should be to apply existing techniques to current CFD simulation capabilities at a large scale, while simultaneously performing foundational research in the development of better reduced-order models and variable fidelity models that are applicable to aerospace problems and can support embedded uncertainty quantification strategies.

(vi) Multidisciplinary design and optimization

The ability to perform CFD-based MDAO relies on the availability of future capabilities that need to be developed between now and 2030. Pervasive and seamless multidisciplinary analyses (MDAs) will require the development of accepted standards and application programming interfaces for disciplinary information and the required multidisciplinary couplings (such as with acoustics, combustion, structures, heat transfer, radiation). In parallel with this effort, it will also be necessary to develop high-fidelity coupling techniques that guarantee the accuracy and stability of high-fidelity, tightly coupled MDAs [31], while ensuring that the appropriate conservation principles are satisfied with errors below acceptable thresholds. Together, the standards and the coupling techniques/software would enable demonstrations of two-way coupled MDAs. A number of capabilities must also be developed in order to enable MDAO with and without the presence of uncertainties (robust and reliability-based design). A major research component is the work needed to endow industrial-strength CFD solvers with both gradient calculation and uncertainty quantification capabilities for use in multidisciplinary optimization.

(d) Grand challenge problems

To enable the assessment of progress in these diverse technical areas and their impact on the long-term goal of enabling superior aerospace vehicle designs, a set of GC problems has been posed. These GC problems purposely have been chosen to be bold, recognizing that they may not be routinely solvable by the target year 2030. However, if success is achieved, this would represent a critical step change in engineering design capability. To this end, the GC problems are chosen to encompass the CFD capabilities required to design and analyse advanced air and space vehicles and systems in 2030 and to represent the capabilities required to enable environmentally sustainable aviation in general. Details of each of the four GC problems are given below.

(i) Grand challenge problem 1

LES of a powered aircraft configuration across the full-flight envelope. This case focuses on the ability of CFD to simulate the flow about a complete aircraft geometry at the critical corners of the flight envelope including low-speed approach and takeoff conditions, transonic buffet and possibly undergoing dynamic manoeuvres, where aerodynamic performance is highly dependent on the prediction of turbulent flow phenomena such as smooth body separation and shock–boundary layer interaction. Clearly, HPC advances alone will not be sufficient to solve this GC problem and improvements in algorithmic technologies or other unforeseen developments will be needed to realize this goal. Progress towards this goal can be measured through the demonstration of effective hybrid RANS/LES and wall-modelled LES simulations with increasing degrees of modelled versus resolved near-wall turbulence structures with increasing geometric complexity. Fully optimized flow solvers running on exascale computing platforms will also be critical.

(ii) Grand challenge problem 2

Off-design turbofan engine transient simulation. This case encompasses the time-dependent simulation of a complete engine including full-wheel rotating components, secondary flows, combustion chemistry and conjugate heat transfer. This GC will enable virtual engine testing and off-design characterization including compressor stall and surge, combustion dynamics, turbine cooling and engine noise assessment. Similar to GC 1, demonstration of advances in accurate prediction of separated flows, complex geometry, sliding and adaptive meshes, and nonlinear unsteady flow CFD technologies will be required to achieve this goal. In addition, advances in the computation of flows of widely varying time scales, and the predictive accuracy of combustion processes and thermal mixing, will be necessary.

(iii) Grand challenge problem 3

MDAO of a highly flexible advanced aircraft configuration. The increased level of structural flexibility that is likely to be present in future commercial fixed and rotary wing aircraft configurations dictates a system-level design that requires the tight coupling of aerodynamics, structures and control systems into a complete aero-servo-elastic analysis and design capability. This GC problem focuses on the multidisciplinary analysis and optimization of such configurations including explicit aeroelastic constraints that may require a time-accurate CFD approach. In addition to the aero-servo-elastic coupling, this GC includes the integration of other disciplines (propulsion and acoustics) as well as a full mission profile. The ultimate goal is to demonstrate

the ability (in both MDA and MDAO) to perform CFD-based system-level optimization of an advanced configuration that requires both steady and unsteady high-fidelity models.

(iv) Grand challenge problem 4

Probabilistic analysis of a powered space-access configuration. The goal of this case is to provide a complete description of the aerothermodynamic performance, including reliable error estimates and quantified uncertainty with respect to operational, material and atmospheric parameters, for a representative space vehicle throughout its flight envelope. This capability will enable reliability predictions and vehicle qualification in the light of limited availability of ground-based test facilities. Demonstration of advances in combustion modelling, off-design performance, adaptive and dynamic overset meshing for stage separation events, unsteady flow, hypersonic flow, CFD reliability, and reliability and uncertainty quantification is required.

Fundamental research towards meeting these GCs will be required in the six identified technical areas, namely HPC, physical modelling, numerical algorithms, geometry/grid generation, knowledge extraction and MDAO. The capability of these combined technologies towards meeting the stated GC problems can be evaluated periodically and used to prioritize research thrusts among the various technology areas.

3. Conclusion and recommendations

Enabling a more efficient air transportation industry of the future with reduced greenhouse gas emissions will require revolutionary advances in air vehicle and associated propulsion system performance, advances that can only be obtained through a more fundamental understanding of the underlying physics, and which will require the development and use of radically more capable physics-based simulation technologies. Despite considerable past success, today there is a general consensus that CFD development for single and multidisciplinary aerospace engineering problems has been stagnant for some time, caught between rapidly changing HPC hardware, the inability to predict adequately complex separated turbulent flows because of the limitations of physical modelling, and the difficulties incurred with increasingly complex software driven by complex geometry and increasing demands for multidisciplinary simulations. The NASA-sponsored study, which forms the basis of this paper, has confirmed this assessment of the current state of the art and provides a strategy for accelerating advances in simulation technology through sustained and focused investment in specific technological areas. However, in addition to developments in these technical areas, national and international stakeholders should consider the following recommendations, which are deemed essential for realizing the important goals of environmentally sustainable aviation through improved high-fidelity simulation technologies.

First, government agencies should develop, fund and sustain basic research and technology (R&T) programmes for simulation-based analysis and design technologies. The presence of focused base R&T programmes for simulation technologies is an essential component of the strategy for advancing CFD simulation capabilities. At a minimum, such programmes should cover the six areas identified in this paper, and these areas should be covered in a very broad

sense, for example with balanced investment ranging from fundamental applied mathematics, physics and science studies, to specific aerospace vehicle application driven projects, and including important interactions between these areas.

Second, relevant government, industrial and academic participants should maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation. In particular, research and technology development must effectively use and leverage simulation expertise and capabilities with focused attention to HPC infrastructure, software development practices, interfaces and standards. Maintaining such a capability will be crucial for understanding the principal technical issues, overcoming impediments and for investigating new techniques in a realistic setting. In order to be sustainable, dedicated resources must be allocated towards the formation of a streamlined and improved software development process that can be leveraged across various projects and institutions, lowering software development costs, and releasing researchers and developers to focus on scientific or algorithmic implementation aspects. At the same time, software standards and interfaces must be emphasized and supported whenever possible, and open source models for non-critical technology components should be adopted.

Next, leading-edge HPC systems should be used and optimized for large-scale CFD development and testing. Access to large-scale HPC hardware is critical for devising and testing the improvements and novel algorithms that will be required for radically advancing CFD simulation capabilities. To this end, large-scale HPC hardware must be made available on a regular basis for CFD and multidisciplinary simulation software development at petascale to exascale levels and beyond, similar to the manner in which HPC is regularly used in important science applications such as climate simulation.

Integrated experimental testing and computational validation campaigns are critical for the advancement of CFD capabilities in the future. Systematic numerical validation test datasets and effective mechanisms to disseminate validation results are becoming more important as CFD complexity increases. Government agencies, often in collaboration with industry, are ideally positioned to lead such efforts by leveraging unique experimental facilities in combination with extensive in-house CFD expertise, thus contributing valuable community resources that will be critical for advancing CFD technology. The development of new experimental testing technologies and facilities is expected to play a continuing role not just in aerospace product development, but increasingly in computational method validation.

Improved collaborations among key research partners and industrial stakeholders across disciplines should be developed, fostered and leveraged within the broader scientific and engineering communities around the world. In an environment of limited resources, achieving sustained critical mass in the necessary simulation technology areas will require increased collaborations with many stakeholders. Mutually beneficial collaborations are possible between national and international government agencies with significant ongoing investments in computational science. At the same time, investments must look beyond the traditional aerospace engineering disciplines to drive substantial advances in simulation technology, and mechanisms for engaging the wider scientific community, such as focused research institutes that engage the broader academic community, should be leveraged.

Finally, the availability of world-class engineers and scientists is critical to the future of clean aviation in general, and of CFD development in particular. The ability to achieve the long-term goals for CFD in 2030 is greatly dependent on having a team of highly educated and effective engineers and scientists devoted to the advancement of computational science. Mechanisms for engaging graduate and undergraduate students in computational science with particular exposure to environmentally sustainable aviation problems such as fellowships and internships can be particularly effective and should be considered wherever possible.

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