

FUTURE CHALLENGES AND OPPORTUNITIES IN AERODYNAMICS

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Abstract

Investments in aeronautics research and technology have declined substantially over the last decade, in part due to the perception that technologies required in aircraft design are fairly mature and readily available. This perception is being driven by the fact that aircraft configurations, particularly the transport aircraft, have evolved only incrementally over last several decades. If, however, one considers that the growth in air travel is expected to triple in the next 20 years, it becomes quickly obvious that the evolutionary development of technologies is not going to meet the increased demands for safety, environmental compatibility, capacity, and economic viability. Instead, breakthrough technologies will be required both in traditional disciplines of aerodynamics, propulsion, structures, materials, controls, and avionics as well as in the multidisciplinary integration of these technologies into the design of future aerospace vehicles concepts.

The paper discusses challenges and opportunities in the field of aerodynamics over the next decade. Future technology advancements in aerodynamics will hinge on our ability to understand, model, and control complex, three-dimensional, unsteady viscous flow across the speed range. This understanding is critical for developing innovative flow and noise control technologies and advanced design tools that will revolutionize future aerospace vehicle systems and concepts. Specifically, the paper focuses on advanced vehicle concepts, flow and noise control technologies, and advanced design and analysis tools.

1 Introduction

The aeronautics industry, particularly the civil aeronautics industry, is frequently described or perceived as a “mature industry” [1]. Thus, support for R&T investments in aeronautics has eroded over the last decade or so. Today, aeronautics can be characterized by

analysis and design tools that are relatively mature based on our current understanding of the physics of flight. Further evidence for this perceived maturity is the fact that today’s transport aircraft have evolved only incrementally over last several decades. Growth in the aviation industry is currently being driven by efforts to reduce costs through improved processes rather than by new technology. New technology must buy its way onto new airplanes being considered by airframe manufacturers around the world; this has led to an emphasis on evolutionary, rather than revolutionary, technology. Additionally, over the last decade, mergers of major aeronautical companies have reduced the number of competing airframe manufacturers. As a result, governmental funding to support aeronautics R&T has often times been labeled as “corporate welfare.”

If, as predicted by international experts, air travel grows by a factor of three in the next 20 years, increased demands for capacity, safety, environmental compatibility, and economic viability will challenge the evolutionary development of technologies and aircraft. Breakthrough technologies will be required both in traditional disciplines of aerodynamics, propulsion, structures, material, controls, and avionics, and also in the multidisciplinary integration of these breakthrough technologies into aerospace vehicle systems. Furthermore, future design methodologies will require an information-technology-driven collaborative design environment. To meet these challenges, continued investments in aeronautics R&T will be required to produce significant advances in aeronautical technologies.

The growth in aeronautical technology tends to be limited by both ideas and our understanding of physics. Many opportunities for technical innovation can be leveraged by the tremendous growth in information technology which, in general, has had far reaching impact on many important areas; however, its impact on aeronautical design tools and the design environment so far has been limited. Innovations in production

technology and its management will also have far reaching impact on aeronautics of the future. Another advancement that will have significant impact on revolutionizing the performance is the integrated design of aircraft. Most of the current design philosophy is based upon what can be called as “sequential design”, i.e. the design by disciplines such as aerodynamic design, structural design, propulsion system integration, environmental impacts (emission/noise), etc. Future design practices will be based upon “integrated design” in an information-technology-driven environment where various design considerations related to aerodynamics, structures, propulsion, emission, noise, etc., will be included in the design space from the onset of the design process.

Although the perception of the aeronautical industry being mature is present in general, it is even more so with aerodynamic technologies. As mentioned before, this perception is driven to some degree by the fact that the aerodynamic design tools have caught up with our understanding of the flow physics. This does not mean that our understanding of aerodynamic flow phenomena is mature. Current tools, combined with significant empiricism and experience, have been successful in designing vehicle systems and concepts, which by themselves have evolved in a highly incremental manner. Even for these vehicles, there are many flow phenomenon, especially at the edges of the flight envelop such as buffet and take-off and landing, that are not well understood, and adequate computational models for these phenomena do not exist in the design methodologies. This results in conservative vehicle designs and compromised performance. When it comes to unconventional designs or revolutionary concepts, which may combine advanced flow/noise/emission control technologies with other advanced technologies such as shape-changing, self-healing materials and structures, the understanding of flow physics falls far shorter than required, and the current analysis and design tools are simply not adequate.

From a technology point of view, as far reaching as the accomplishments of flight have been in the 20th century, they have been achieved without fully understanding the physics of flight; it is hard to comprehend what could be done if one really understood the physics. This is the challenge for the 21st century. Nano-scale vehicles navigating the human circulatory system and planetary exploration vehicles flying the atmospheres of outer planets are just two visions of potential flight innovations. In this paper, we will focus primarily on challenges and opportunities in

aerodynamic technologies and those technologies which directly impact aerodynamic technologies. Specifically, we will address advanced vehicle concepts, flow and noise control, and advanced design and analysis tools.

2 Advanced Vehicle Concepts

With growing air travel, societal needs for increased safety and reliability, reduced noise and emission, reduced travel time, and more affordable travel will become even more critical in the future. To increase the capacity of the current air transportation system, the aircraft industry is already developing larger aircraft with capacity as high as 600 passengers and, maybe, even 800 to 1000 passengers. Research is also being conducted to improve the efficiency of aircraft operations. However, these approaches will simply not be adequate to meet the demand. Increased airport congestion and flight delays will cause extreme frustration amongst travelers. For short distance travelers, air travel simply will not remain an effective option from cost and timeliness point of view. The traveler in the 21st century will expect an integrated, hassle-free, cost-effective travel system that can be used in a time-efficient manner. Obviously, the evolutionary approach for increasing the capacity of the current air transportation systems is not a solution. There is a need for a revolutionary approach to both the air transportation operations as well as the development of large and small aircraft. To revolutionize the operational efficiency of the air transportation system requires insertion of new technology such as an integrated navigational system that allows around-the-clock, all-weather, environmentally unobtrusive flight from major airports as well as thousands of small general aviation airports. However, in this paper we will focus only on development of advanced aircraft concepts and aerodynamic technologies with revolutionary performance.

As mentioned earlier, the aircraft industry is already working on very large capacity transport aircraft. Aircraft of this size (1 to 1.5 million pounds) will have to be extremely fuel efficient, generate low noise levels, and be able to take-off and land on conventional runways. Fuel efficiency can be obtained by developing new engines with ultra high bypass ratios and by reducing drag through efficient aerodynamic design and by using technologies such as hybrid laminar flow control (HLFC). Research to date has demonstrated that HLFC is a viable technology for reducing drag and

improving fuel burn, but further research is required to develop it at the large Reynolds numbers associated with these very large transports. Airframe noise will be of particular concern on these very large aircraft. Research will need to be conducted to develop better methods of identifying sources of noise and suppressing or eliminating them by both active and passive methods, especially during take-off and landing. This acoustic research, like the aerodynamic research, will need to be conducted at high Reynolds numbers. Another factor that greatly affects the weight of an aircraft is the performance of its high-lift system. In general, the more complex the high-lift system the more it weighs. Systems with fewer elements (i.e., flaps, slats, etc.) utilizing either passive or active boundary layer suction or blowing to delay separation of the flap boundary layers will be needed to meet runway length constraints. Smart structures, together with flow control technology, will play a vital role in the needed improvements in control surface effectiveness and their size and weight. These technologies will also allow for continuous recontouring of the wing surface during cruise, thus further reducing the drag and improving fuel efficiency.

In addition to simply increasing the capacity of current aircraft configurations, totally new concepts need to be developed that produce a step increase in the performance. These configurations should offer simultaneous opportunities for mitigation of both the drag due to lift and wake vortex hazard and for synergistic propulsive and aerodynamic interactions. Examples of such concepts include blended wing body aircraft [2], strut-braced wing aircraft [3,4], and C-wing aircraft [5], all of which have the potential for lift to drag (L/D) ratios in excess of 30.

Another consideration for the future is an economically viable, environmentally compatible, large supersonic transport. A strut-braced configuration with multi-body, extreme arrow wing planform is a possible example of a supersonic transport with revolutionary performance [6]. This planform has lower wave drag, and extensive laminar flow can be achieved on the wing due to low wing Reynolds numbers. The aircraft has the potential for cruise L/D of up to twice the value targeted in the NASA High Speed Research Program (i.e., L/D ~ 18-20).

Another part of the solution to meet increased air transportation demand, especially for people traveling less than 500 miles, is personal air vehicles that make use of thousands of general aviation airports and better utilize the low-level air space by opening up skyways. These personal air vehicles (small aircraft, rotorcraft,

tiltrotors, or converticars) will be crash proof and will be able to operate under all weather conditions with little training required to fly them. The engines for these aircraft will be highly reliable and environmentally efficient. Ultimately, they will be zero-emission aircraft using fuel cells, and their flight will be unobtrusive to the community from the noise point of view. Innovations in flow control technology will eliminate wing stall, compensate for excessive atmospheric turbulence, and enable automatic take-off and landing. In addition to desired aerodynamic performance, the aircraft will have to be economically affordable, initially by a small group of people and, eventually, by the average person. This concept of pilotless, zero emission, runway independent, all weather, unobtrusive flight may sound far-fetched at present, but just consider the accomplishments of flight in the last century.

In the military arena, new vehicle systems will include more unmanned combat air vehicles (UCAVs) and micro-flying machines with a variety of sensing technologies. With a potential service life of 30 to 40-plus years and a progressive migration to UCAVs in all major roles, it is possible, even likely, that the JSF, F-22, Eurofighter, etc., are the last piloted combat aircraft to be developed. Today, UCAVs are being considered to carry a weapons payload over long range through hostile enemy environment. This has many benefits such as reduced weight, higher g capability, simplified design and safety requirements, and reduced cost due to remotely locating the pilot. However, the aerodynamic development of UCAVs should not be very different from today's aircraft since it still has to be designed for high performance, precision, and appropriate handling qualities.

For further discussion on advanced concepts, see References 7-9.

3 Adaptive Flow Control

Even though flow management around complex aircraft components using techniques such as vortex generators, riblets, suction, blowing, etc., has been examined for decades, much of the focus has been on passive flow control. However, recent advances in materials, electronics, miniaturized sensors, and actuators and increased understanding of three-dimensional unsteady flow physics have opened the door to new innovations in actively controlling macro- and micro-scale flow characteristics. This is truly a growth area in

aerodynamics that will revolutionize the aircraft of the future and will allow for step increases in aerodynamic performance while, at the same time, dramatically reduce noise and emissions. A broad range of active and passive flow control techniques are currently being developed for local and global flow management with many possible applications such as separation control for enhanced aircraft controls effectiveness and simplification of high-lift system, laminar and turbulent flow control for drag reduction, and “virtual” shaping of an aerodynamic surface for adaptive performance optimization (i.e., to ensure that the aircraft is always flying in the optimal configuration of a particular flight regime). With the help of flow control, aircraft structure could be freed from flight control functions, thus dramatically reducing the weight of the aircraft.

An optimum flow control system will be closed-loop (also defined as adaptive control system) i.e., a system that senses the flow, compares it to the desired conditions to determine required actuation authority, and then implements the control through actuators. The time scale for this control process will be commensurate with the required speed of control effectiveness. The understanding of, and requirements for, this enabling technology are still in the embryonic stages; however, critical to the success of developing and implementing such active flow control technology are:

- Understanding of three-dimensional unsteady, laminar and turbulent, attached and separated flows and their temporal and spatial numerical simulation
- Multidisciplinary integration of fluid dynamics, materials, structures, and controls
- Micro- and nano-sensor and actuator technology

While research continues in these areas, both active and passive control concepts are currently being developed based upon the current understanding, experimental testing, empiricism, and intelligent use of available tools. A brief description of several current and future flow control techniques and concepts will now be provided.

3.1 Flow control for drag reduction

One of the ways to design a low-drag wing is to maintain laminar flow on a significant fraction of the wing wetted area. This is known as the laminar flow control (LFC). Significant progress has been made in this technology for applications to small and large, subsonic and supersonic aircraft. There are several ways in which LFC can be achieved. The simplest of these is the natural laminar flow control (NLF) which employs a favorable pressure gradient to delay the boundary layer transition process.

Inherent in practical NLF wings is low sweep (typically less than 15 degrees) for small to moderate size aircraft. The extent of the laminar flow can be further increased by applying suction or cooling on the surface. For wings swept to higher angles for high speed flight, the flow on the wing becomes three-dimensional and a new cross-flow instability in the boundary layer makes NLF design ineffective since favorable pressure gradient alone is not sufficient in controlling the cross-flow instability. Its control usually requires the use of suction on the surface of the wing. Another LFC option for large subsonic and supersonic aircraft is to combine suction with NLF, thus creating a hybrid laminar flow control (HLFC) concept. Combining NLF with suction reduces suction requirements and system complexity. HLFC has been successfully demonstrated subsonically in flight on a B757 [10,11] and supersonically on an F16-XL [12].

Both NLF and suction LFC seek to delay transition by suppressing the growth of unstable disturbances in the laminar boundary layer that are known to cause transition. A more fundamental approach to LFC is, therefore, to target the very genesis of these instabilities—known as the process of boundary-layer receptivity whereby external disturbances are internalized in the boundary layer. However, due to practical difficulties associated with canceling naturally occurring instabilities via artificial excitation of out-of-phase (but otherwise identical) disturbances, alternative ways of implementing receptivity control must be explored. A recently demonstrated novel approach involves artificial excitation of subdominant instability modes that suppress the growth of the otherwise dominant modes via nonlinear mode competition [13]. LFC via receptivity control is currently in early stages of development and requires an improved understanding and modeling of the receptivity process. However, once fully developed, it could greatly simplify the implementation of laminar flow control by eliminating the need for suction and associated systems such as piping, suction pumps, etc.

3.2 Flow control for boundary layer separation

Boundary layer separation occurs on many components of aircraft under a variety of flow conditions and it causes severe aerodynamic performance penalties. Vortex generators [14] have been successfully used to control separated flow by inducing longitudinal vorticity in the flow. Large vortex generators have been used on the aft portion of an aircraft to improve the overall performance of the aircraft whereas micro vortex generators (less than one-half of the boundary layer

thickness) have been used on the wings of production aircraft to prevent flow separation, primarily during take-off and landing. These vortex generators are passive in nature and remain deployed at all times, whether needed or not. This may result in parasite drag due to interaction of vortex generators with the external flow during the part of the flight when they are not required such as during cruise. More recently, active fluidic vortex generators have been proposed and tested. These fluidic vortex generators can be used not only during aircraft take-off and landing for separation control but can also be used during cruise for drag reduction by inducing slip velocities on the surface.

One variety of fluidic actuator consists of a cavity with a flat plate asymmetrically aligned at the top face such that wide and narrow gaps are formed [15]. Wind tunnel tests have shown that a jet-like flow can emerge from the small or large gap depending upon the scaling parameters of the actuator. It has also been shown that with the narrow gap width held fixed and varying the wide gap width, frequency, and motion of the plate, a vertical jet-like flow, a wall-jet, an angled jet-like flow, or a vortex flow could be produced. Thus, this active fluidic vortex generator concept has the potential of providing active flow control under multiple performance requirements. Obviously there is a need to explore and develop this and other possible actuator concepts. Micro Electro Mechanical Systems (MEMS) technology or macro scale technology with embedded MEMS devices as the active elements represents the enabling technology in the development of such actuators [16]. In addition, full exploration of the design space of such devices requires the formulation of an efficient computational model for this type of actuator.

A significant body of recent work (e.g., Amitay et al. [17]) has demonstrated the use of micro-sized piezoelectric actuators for flow manipulation. The proposed piezoelectric actuator has a net mass flow of zero, but peculiar to it is a jet-like flow field that emerges with actuation of the device. It is because of this feature that it has also been called a synthetic jet actuator. Such actuators have been shown to generate velocities from a fraction of a meter/second to 10's of meters/second over frequencies ranging from Hz to kHz. With further development, the zero-net-mass jets may potentially lead to aerodynamic performance benefits through enhanced lift on wings, drag reduction during cruise through advanced active LFC, and on-demand control moments, thereby eliminating or reducing the need of traditional flap/slat hardware. The future research in the zero-net-mass actuators includes determination of (1) correlation

between the actuator characteristics and resulting flow field, (2) consequences of the interaction of the jet-like flow with the turbulent boundary layer, (3) correlation of the actuator characteristics with the near-field surface pressure for control law development, and (4) resulting lift and control moments for unswept and swept wing with quantification of potentially adverse effects on the overall acoustic signature.

3.3 Flow control for high lift

Conventional high-lift systems are used during take-off and landing operations to generate sufficient lift at low speed. However, these multi-element systems incur a significant weight penalty and added aircraft maintenance. To generate high lift, it is necessary to increase circulation around the wing. In a conventional high-lift system, this is accomplished by deflecting the control surfaces to increase effective wing camber. Another approach would be to increase circulation around the wing by blowing air through a slot on the upper wing surface, just upstream of the rounded trailing edge. An even better way to achieve increased circulation is through the use of unsteady blowing. Recent wind tunnel experiments have demonstrated that unsteady blowing is effective in controlling separation at Reynolds numbers corresponding to take-off and landing conditions of a subsonic transport [18]. This technique works by promoting mixing between the lower momentum fluid near the surface and the higher momentum fluid at the edge of the separated region, thus bringing the higher momentum fluid close to the surface and making the boundary layer less susceptible to separation. Unsteady blowing has the advantage of controlling separation without performance degradation at off-design conditions and has been shown to be significantly more efficient than steady suction or blowing traditionally used for separation control. Although an oscillatory blowing valve was used to generate the periodic disturbance in wind tunnel experiments [19,20], any type of fluidic actuator could also have been used. These experiments have identified actuator development as a key enabling technology that must be matured before unsteady blowing can be implemented on real systems. In a future wind tunnel experiment at NASA Langley on a multi-element airfoil, a piezoelectric actuator will be used on the trailing-edge flap in place of the oscillatory blowing valve to generate the control. McLean et al. [21] provides a cost/benefit analysis of replacing the conventional high-lift system with a flow control high-lift system.

4 Noise Control

Noise control remains an important aspect of aircraft design. NASA has set an aggressive goal of reducing aircraft noise emissions by another 20 EPNdB from the 1997 baseline over the next two decades. Such dramatic reductions are absolutely necessary to allow for the projected growth in air traffic while ensuring compliance with the increasingly stringent community noise standards. Interior noise reduction is also warranted to improve passenger comfort, reduce crew fatigue, and increase safety. Considering that current aircraft fleets are already about 30dB quieter than the first turbojet powered airliners, extremely innovative approaches will be required to achieve the projected noise reduction targets without accruing undesirable penalties in aerodynamic or propulsive performance. Again, it is somewhat premature to speculate on what precisely these approaches would be; however, it is certain that identification and successful implementation of these approaches will require a deeper understanding of both the underlying physics of noise generation and propagation (especially for broadband noise sources) and the global interplay between acoustic, aerodynamic, propulsive, and structural subsystems. A few of the many promising noise reduction concepts that are currently under investigation are outlined in this section.

4.1 Fan noise

The aircraft noise is primarily produced by two sources, the engine and the airframe. In case of modern, high-bypass-ratio engines, the turbofan is a major contributor to the noise and consists of both tonal and broad band noise. It can be controlled either by directly attacking the noise sources, via attenuation in the duct before it escapes the nacelle or by shielding by the airframe en route to the receiver. A common approach for fan noise reduction involves geometric modifications to influence the rotor-stator interaction. A more promising concept to directly influence the mean wake characteristics by trailing edge blowing has been shown to reduce the rotor wake/stator interaction by up to 4 dB. Active control efforts aimed at both source level control (via actuators mounted on the fan cascade) and propagation level control (via sources along the nacelle surface) have also been initiated in recent years. Conventionally, propagation level control of fan noise has been achieved using acoustic treatment panels (i.e., liners) in both inlet and exhaust ducts. However, newer engine designs with lower length-to-diameter ratios have created the need for a step increase in liner bandwidth and suppression efficiency to achieve the required attenuation within the

reduced length available for treatment. Recently proposed innovative liner concepts include either self-adjusting (i.e., smart) liners based on MEMS technology or even a conventional, passive liner with in-situ control of an impedance controlling parameter, such as open area ratio of the liner perforate and bias flow across the liner. As a result of the progress made in predicting and controlling the tonal content of turbomachinery noise, broadband noise has become the current focus of research and represents the final frontier in understanding the main physics of turbomachinery noise generation. Both detailed measurements of the turbomachinery flow field [22] and accompanying numerical simulations are needed to pin down the precise nature and hierarchy of the various sources involved, so that more effective noise reduction measures can be identified, tested, and optimized. There exists a significant scope to exploit the physical similarities between broadband fan noise and airframe noise sources in this regard.

4.2 Jet noise

Jet noise is yet another source of propulsive noise. Although significant reductions in jet noise have been achieved since the first turbojets were placed in service during World War II, jet noise still remains a significant contributor to noise during full power take-off. Jet noise is controlled via a combination of enhanced mixing (which rapidly decays the plume and reduces the low-frequency noise), reduced characteristic jet dimension, and increased mean shear near the nozzle exit plane (which increases the high-frequency noise that is more easily attenuated via atmospheric absorption). Passive devices such as tabs and chevrons have been shown to reduce jet noise by up to 2 EPNdB in realistic nozzle configurations.

Other novel jet noise reduction concepts currently under examination include suspension of a flexible filament in the plume [23] and water injection to alter the turbulence characteristics of the jet. Due to the inherent need for water supply, however, the application of the latter concept will require trade-offs between the quantity of water required and the noise reduction. Active control of jet noise, via unsteady actuators, such as glow discharge devices, mounted near the nozzle exit is another attractive option from the standpoint of maintaining optimal aerodynamic performance under a wide range of operating conditions. However, in addition to addressing the technical issues involved in this form of control, there is a need for examining the

robustness of such devices in the harsh environment of a high-temperature jet exhaust.

A more complete understanding of jet noise sources, particularly at subsonic speeds, will greatly aid the development of more effective noise suppression concepts. Currently, the dominant source of subsonic jet noise is associated with the smaller scales of turbulence. Given the tremendous difficulty in both measurements and computations of the small-scale structures, however, there is no direct evidence to support this belief. Clearly, the capability to either compute and/or measure, process, and extract the missing multi-point statistics of turbulent fluctuations will represent a major breakthrough towards improved understanding, prediction and, hence, suppression of subsonic jet noise. During the past decade, there have been several exciting developments across a broad spectrum of prediction methodologies for jet noise. Together, such advances in computational fluid dynamics (CFD), computational aeroacoustics (CAA), and multi-point measurement of turbulent fluctuations represent a promising outlook for first-principles-based prediction (and, hence, suppression) of jet noise.

4.3 Airframe noise

With continued success in engine noise reduction, airframe noise has emerged as a potentially significant contributor to the overall acoustic emissions, particularly at approach conditions. The dominant sources of airframe noise are known to be associated with unsteadiness of the separated and/or vortical flow regions around the high-lift system and the landing gear of the aircraft. The myriad of three-dimensional features that may contribute to flow unsteadiness and the importance of surface geometry in scattering these vortical structures into sound make airframe noise an extremely complex and challenging problem. A major focus of the recent work on airframe noise has been on noise associated with the high-lift system, particularly noise generation near a flap side-edge [24]. Using a combination of detailed measurements and Navier-Stokes computations related to both the local flow field and the far-field acoustics, a NASA-industry team was able to correlate different parts of the far-field spectra with specific near-field features. Such features include instability modes of the shear layer(s) associated with flow separation near the side-edge and edge vortices created by the roll-up of the shear layer. Armed with the physical understanding of the noise sources involved, several passive edge treatments, such as a porous flap tip, were tested and shown to result in noise reduction of

up to 4 dB. A similar effort for the slat noise led to the discovery that a prominent, high-frequency hump in the slat noise spectrum is caused by vortex shedding from a seemingly sharp slat trailing edge. The otherwise broadband noise was shown to be associated with unsteadiness of the separated flow on the lower slat surface—a finding that again helped in cutting the noise levels by over 5 dB.

There exist other potential ways of reducing the flap/slat-induced noise, which have not been examined in detail as yet. These include using steady suction or blowing to influence the location of strongly unsteady flow features (such as side-edge vortices, or reattachment location on the underside of a flap) relative to geometrical irregularities such as surface edges and corners. A passive technique that appears well-suited for practical application is to eliminate or minimize the extent of inboard side-edges via flap geometry based on the continuous mold line technology concept.

Acoustic measurement techniques based on novel microphone array configurations have played a crucial part in the recent breakthroughs in airframe noise via identification of the dominant noise source locations throughout the frequency range of interest and, therefore, further development of array technology is needed. Numerical simulations, both steady and unsteady, of the airframe flow field will assume an increasingly important role in the next phase of airframe noise research. At the same time, detailed measurements of the unsteady source region will be equally necessary to validate such computations. Ongoing work on identification and control of individual noise sources will provide a strong foundation for investigating additional noise generation/modification associated with interactions between multiple airframe components (e.g., interaction between the wake of a landing gear and the flap) and installation effects involving propulsion-airframe integration, including the interplay between propulsive noise sources and airframe components (e.g., jet interaction with a flap).

In summary, the successes of prior noise-reduction efforts have already brought us to the point where each additional dB reduction will be increasingly difficult to achieve. However, given the need for continued noise reduction, extremely innovative approaches will be required to achieve the projected targets during the next two decades. Also, as the dominant tones are successfully reduced using technologies already developed, additional noise reductions will come from controlling the broadband noise. Because of the origin of the broadband noise in flow turbulence, advances in

flow and noise control technologies will have to be increasingly synergistic. Such synergies could be either at the modeling level (e.g., physical similarities between synthetic jet actuators and duct acoustic liners could permit overlapping design tools) or extend to implementation level (e.g., micro-blowing could serve the dual purpose of reducing nacelle drag and controlling acoustic impedance).

5 Advanced Analysis and Design Tools

The primary purpose of engineering research and development is to provide new information and tools for the analysis and design of new systems and concepts to meet certain human needs. These tools could be used for either analysis or design. A clear distinction can be drawn between analysis and design tools. Analysis tools allow the engineer to diagnose a problem whereas design tools are used in conjunction with analysis tools to improve an existing product or to create a new one.

The traditional design process for an aerospace vehicle can be broken down into several stages: conceptual design, preliminary design, and final design. Conceptual design involves the development of concepts to meet the intended mission, leading to the eventual selection of a preferred concept. Typically, this stage involves the application of low-fidelity but very fast tools to examine a large design space, with many design iterations performed quickly. The tools may provide approximate overall performance estimates or approximate changes in performance due to changes in design. In preliminary design, a limited number of iterations are performed, wherein conflicting requirements from various disciplines are resolved to produce an overall design that can meet the mission requirements within schedule and cost constraints. At this stage, higher fidelity tools are used to assess the performance within sufficient accuracy. In the final design stage, the design is optimized for performance, and benchmark performance data are produced over the design space using the highest fidelity tools. The detailed design is characterized by the definition of the actual pieces to be manufactured as well as the fabrication and assembly processes required.

As in any industry, the emphasis in the aerospace design market is on cost reduction to keep the product affordable, risk reduction to ensure mission objectives are met, and shortening the time-to-market to gain a competitive advantage. As detailed by Raj [25], there are two fundamental deficiencies inherent in the traditional design process which work against these goals. The first deficiency is that as much as 70 to 90

percent of the life-cycle cost of an airplane is locked in during the early stages of design, the period when the fidelity of the engineering data is lowest and many of the life-cycle costs (e.g., manufacturing and support) are modeled crudely, if they are modeled at all. The second deficiency is that the sequential nature of the process leads to long cycle times.

To address the deficiencies of the traditional design process, industry has embraced concurrent engineering practices, as embodied by the concept of integrated product and process development (IPPD) [26]. IPPD is characterized by the integration of all aspects of product development, including design, manufacturing, and support so that all requirements and constraints are considered from the start of the project. Of particular significance is that vehicle life-cycle costs become a design consideration at the outset. Within the IPPD context, the design effort becomes an integrated multidisciplinary process, providing the potential to design for the minimization of life-cycle costs under the constraint of meeting mission objectives. Critical to the success of IPPD is the capability for rapid generation and synthesis of higher fidelity information from all disciplines at the beginning of the design process. To facilitate the implementation of a process like IPPD, NASA has initiated a program called Intelligent Synthesis Environment. The basic goal of such a design process and environment is to generate and provide the information “to allow designs at the speed of the designer” rather than of the design tools.

5.1 Revolutionary tools for revolutionary concepts

There are some important implications of using low fidelity tools in the conceptual design phase, especially when the desire is to develop revolutionary aerospace concepts. Most tools used in the conceptual design phase rely on some existing knowledge base, developed from previous designs. These tools are incapable of generating revolutionary new designs, as by definition they rely on previous design experience. Gaps in the designer’s knowledge typically lie at the limits of the flight envelope. Where there is limited prior knowledge, design tends to be conservative and incremental. Revolutionary concepts require tools that allow the designer to explore a larger design space more rapidly and with sufficient accuracy, if radical improvements in flight vehicle technology are to be obtained.

Limitations in testing techniques and facilities also play a role in restricting a designer’s options. Goldhammer and Steinle [27] point out that in the design of transonic aircraft, which is mistakenly considered by

many to be a “mature technology,” testing at less-than-flight Reynolds numbers puts limits on wing design strategies that could be pursued. This is even more true for the high-lift system design which is very sensitive to both Reynolds and Mach number effects. Traditionally, high-lift system design has been done by low Reynolds number testing and the use of empirical correlations to predict full-scale performance. This leads to considerable conservatism in design to reduce the risks in the absence of any real database at appropriate conditions.

The requirements for design tools are necessarily driven by the design objectives and the stage of a design. A design tool should allow the designs to occur at the speed of the designer. At the conceptual stage, the design space is very large and the design changes are large and discrete. At the preliminary design stage, the changes are more likely to be small and continuous; more like perturbations relative to the changes at the conceptual stage. From a designer’s point of view, how early a design tool can be used in the design process is determined based upon the degree to which it is capable of handling large changes in topology and shape, including the swiftness with which the problem can be set up and the computations performed.

5.2 Design methods

Design methods can be divided into several categories, namely, parametric-based design methods, knowledge-based design methods, and optimization-based design methods. Parametric-based design methods are used to study the effect of various design variables, mostly by varying one variable at a time. Obviously, as the number of design variables increases, this method becomes more impractical. Further, this method does not permit the designer to assess the interaction of the design variables. More recently, sophisticated statistical methods, such as Modern Design of Experiments (MDOE) [28], are being used to study multiple variables in a design process within reasonable time and resources. The added benefit of the MDOE approach is that it also drives the measure of success towards defining the objectives of the test or computations ahead of conducting the study along with uncertainty requirements for the design.

Knowledge-based design methods are founded on a mathematical relationship that relates the sensitivity of the design objective to the design variables. The iterative, approximate nature of the method makes it possible to conduct useful design iterations on partially converged solutions, thereby limiting the computational work requirements and increasing the feasibility of using

high-fidelity computational tools. A state-of-the-art example of a knowledge-based design method for aerodynamic design is the Constraint Direct Iterative Surface Curvature (CDISC) inverse design method of Campbell [29], which has been indirectly coupled with numerous flow solvers, including high-end computational fluid dynamics (CFD) codes. CDISC is based on an approximate relationship between a pressure distribution profile and surface curvature (subsonic/transonic flow) or slope (supersonic flow). Multiple flow constraints, including global constraints (e.g., span load distribution), are handled iteratively in an attempt to satisfy all requirements. Despite many approximations in the method, it has been applied successfully to numerous design efforts on realistic aircraft configurations including wing design with propulsion airframe interaction effects [30,31], installed nacelle designs for hybrid laminar flow [32], and multi-component and multi-point designs [29].

The advantages of knowledge-based design methods are that they are relatively easy to set up, run relatively quickly, and the cost of a design is on the order of the cost of a computation. The obvious disadvantage is that the approach is confined to an objective function that is evaluated on the surface defined by the design variables, e.g., inverse design is not applicable to the problem of designing a nacelle strake to improve wing performance.

The optimization-based design methods are used to obtain optimum design with respect to design variables. Most commonly used optimization algorithms are gradient based and require chain rule differentiation of the objective function with respect to the design variables which, in turn, requires sensitivity derivatives. These derivatives can be generated automatically in the computational code from preprocessing tools such as ADIFOR [33], hand coded, or found by using the complex variable technique [34]. Much of the current work in gradient based optimization methods for aerodynamics is focused on the adjoint formulation [35,36], which is suitable for problems where the number of design variables is large relative to the number of aerodynamic constraints and objective functions.

While the options for defining and setting up a problem for single-discipline optimization are many, the complexity is compounded many times for multidisciplinary design optimization (MDO). The recent article by Zang and Green [37] provides a research and methods perspective on MDO, and the paper by Giesing and Barthelemy [38] provides an industry perspective on MDO applications and needs.

5.3 Future design tools

In most of the aerodynamic design so far, configurations are developed without formal considerations of a number of important effects which, when considered as an afterthought in the design, result in compromised performance. Examples of these are propulsion airframe integration effects, noise control effects, etc. To achieve optimum performance, future revolutionary or unconventional aerospace configurations will require design tools that allow design for propulsion airframe interactions, design for noise signature control, design for aeroheating loads, design for surface shaping for separation control, design for flow control effector arrays, etc. These design tools will be required to specify target accuracy in the performance parameters, such as lift or drag, based upon rigorous error estimates in the solution from a computational tool. Recent approaches in design tools include optimization for uncertainties based upon methods such as reliability-based design [39] and robust design [40]. Reliability-based design methods focus on the probability of failure due to a wide variety of uncertainties, including those in the design parameters, the operating environment, and the computational models. Robust design methods search for regions in the design space where the design remains effective in a broad neighborhood of the "optimal" point.

5.4 Computational tools

For designs to occur at reduced cost, time, and risk, it is necessary to improve the computational tools for increased speed and accuracy. Along with increased accuracy, it is also necessary to quantify uncertainty bounds of the numerical solution. Rubbert [41] has pointed out that CFD algorithm development has historically focused on accuracy improvements at the cost of increased turn around time, thus limiting the number of aerodynamic design cycles possible. The greatest aerodynamic difficulties lie at the boundaries of the design space, where fast but low-fidelity tools are incapable of providing accurate solutions. It is, therefore, necessary to balance changes in accuracy and speed so that improvements in one do not deteriorate the other. Radical improvements in the convergence rates of Reynolds-averaged Navier Stokes (RANS) methods means that they can be used earlier in the design process, increasing the accuracy of preliminary design studies. Furthermore, unconventional configuration concepts lying outside the experience base of the designer can be explored more readily and with greater confidence during early design stages.

CFD algorithms were developed rapidly during the 70s and early 80s, but since then the algorithms have improved only incrementally with limited change in their speed. Over the last fifteen or so years, most of the increase in computational speed of RANS-based solutions has come from improvements in computer memory and speed. The ability to analyze a full configuration on a high-end workstation would revolutionize the aerodynamic design process; however, this would require an improvement of two to three orders of magnitude in total solution time of a RANS computation.

The theoretical framework has been shown to exist for multigrid methods for such revolutionary improvements. These methods are well known to be optimal for elliptic partial differential equations. They have the property that the solution of the difference equations can be achieved to within the discretization error of the scheme in $O(n)$ operations. For the Navier-Stokes equations, Brandt [42] argues that multigrid methods based on a decomposition of the governing equations into their elliptic, parabolic, and hyperbolic factors ought to exhibit convergence rates equivalent to those for pure elliptic problems. Such optimally convergent methods would be as much as two orders of magnitude faster than current solvers. This is sufficient to reduce solution time for high-lift configurations to the point where a RANS solver can become a usable tool in a product development environment.

There have been several demonstrations of optimally convergent multigrid methods for the Euler equations on general grids [43,44], and for the Navier-Stokes equations for simple geometries [45]. Recent theoretical developments on factorizable discretizations for compressible flow [46] are a very encouraging sign that such optimally convergent methods are a real possibility for the solution of the full Navier-Stokes equations. However, much work remains in developing a production computational tool based on these methods.

Another important issue with computational tools is to be able to quantify the accuracy of the numerical solution or, in other words, be able to put uncertainty limits on the solution. This is necessary so that the designer can predict the performance of a flight vehicle with known, quantitative accuracy. To date, even in the design of transonic transport aircraft, cruise drag can be determined only to within 10-20 counts or 3.5 to 8 percent of the total drag. Current RANS codes cannot achieve this level of accuracy in off-design conditions such as buffet onset or high-lift configurations where the flow is highly separated and unsteady. Improvements in

absolute accuracy require adequate resolution of all the relevant scales in length and time. Even though the Navier-Stokes equations can predict the unsteady, separated flow for a complete configuration, in practice it is not yet feasible to do so due to the lack of computer resources which are required to resolve all the relevant scales in such flows. It is, therefore, necessary to resort to modeling of unresolved scales. Thus, the improved accuracy also demands improved transition onset prediction and extent modeling, improved turbulence models, adaptive grids and error estimation, and resolution of appropriate geometric features of the configuration.

The most difficult accuracy and reliability challenge facing the advanced CFD methodologies is the accurate prediction of flow separation onset and progression. Being able to identify when and where separation (either local or massive) will occur at flight Reynolds numbers is the essence of the aerodynamic design problem and presents a major roadblock to the introduction of new aerodynamic concepts and technologies (such as flow and noise control) into the design process. The ability to predict separation onset and its extent is also critical to reducing the aerodynamic design cycle time by reducing the required wind tunnel testing. Significantly improved boundary layer transition and turbulence models across the speed range and up to flight Reynolds numbers will be required. Advanced measurement techniques for investigating and improving the understanding of the physics of unsteady viscous flow at appropriate flight Reynolds number will be critically important in meeting this challenge. Much of this physics-based research will require the use of high Reynolds number facilities such as the National Transonic Tunnel at NASA Langley and the European Transonic Wind Tunnel.

The most currently available transition onset prediction methods use an empirical N-factor method, which is based on the linear boundary layer stability theory [47]. These methods require a transition onset database from quiet wind tunnels and flight tests to correlate the value of N. Since there are very limited flight test data available and since most wind tunnel data are taken in noisy environments and at non-representative flight conditions, the transition onset prediction methods are not reliable. There is also a need to model the extent of transition region before the viscous flow becomes fully turbulent. Most computational codes today either model this transition region in some adhoc manner or use models that were developed for incompressible flow. The turbulent boundary layer in most codes is still modeled by either

an algebraic, one-equation, or two-equation eddy-viscosity model. These models are not capable of accurately predicting complex flow interactions unless very finely tuned for a narrow range of flow conditions. However, algebraic or full Reynolds stress models [48] are currently making their way into some of the prediction codes. These models do have the ability to model complex interactions but need further research to make them robust and computationally efficient. In general, significant improvements in accuracy and robustness are still needed in transition and turbulence modeling to enhance the accuracy and reliability of computational predictions.

Obtaining sufficient resolution of the flow requires the development of adaptive grid methods to avoid extreme grid sizes. Often, a small geometric feature gives rise to a large non-local flow effect. For example, a strake on a high-bypass engine nacelle is often used to generate a vortex to control the spanwise development of the flow over a swept wing at CL_{max} . Although the vortex is a compact flow feature, the need to accurately resolve it stems from the fact that it has enormous impact on aircraft performance. Adaptive grid methods require a means for estimating the error in order to refine or coarsen the grid appropriately. Considerable work on error estimation using adjoint methods is being done by Giles and Pierce [49] and Venditti and Darmofal [50]. These error estimation methods are based on a sound mathematical approach to identify precisely which parts of the grid have the most significant impact on the error in integral quantities such as lift and drag. Error estimation methods in computational tools should provide the designer with quantitative estimates of the accuracy of a given design.

5.5 Certification by analysis

The ultimate goal of computational tools is to be able to certify a new technology or vehicle concept without the use of extensive ground or flight testing. This will require the ability of the computational tools to predict absolute performance within known uncertainty bounds over the entire operating conditions. Further, since hardly any technology or concept depends upon a single discipline, certification by analysis will inherently be based on a multidisciplinary capability to account for a wide variety of interdisciplinary interactions. However, development of such a capability will produce desired competitive advantage by rapid and timely insertion of new technology and concepts in the market. For CFD tools within this multidisciplinary capability, rapid turnaround would be provided through the use of an

optimally convergent multigrid method. Accuracy considerations would be addressed through the use of advanced transition and turbulence models, or perhaps a suite of such models with the capability for automatically characterizing the flow and selecting the most appropriate model for viscous flow regions. Sensitivities provided by the code would be used for solution adaptive gridding procedures, error quantification, and obtaining stability and control derivatives. Excursions through the flight envelope would use rapid reanalysis capabilities [37] for changes in flow conditions and control surface settings.

Perhaps the most limiting deficiency of the system described above is that while error bounds on all the computations would be provided, those bounds are on the computational error rather than the error between the computed solutions and the real world situation. Consequently, the development of a certification by analysis capability is closely linked to extensive code validation efforts to establish real error bounds. However, the wide variety of flow interactions for full configurations, along with limited data in the areas of greatest complexity, make it difficult to assess the validity of computational codes in predicting specific phenomena. This problem becomes even more acute when the configurations are very different from the ones on which a lot of experience base exists. The appropriate, efficient way to ensure credibility in CFD simulations for drastically different designs is through validation of the tools for a variety of benchmark, interactional flows at flight Reynolds and Mach numbers. This is what drives the need for flow validation experiments that target specific flow interactions, rather than full configurations [51].

5.6 Future role of wind tunnels

As the computational tools become increasingly reliable in predicting system performance, the role of wind tunnels will shift towards physics-based testing for increased understanding of various flow phenomena and for developing extremely high fidelity data for physical model development and code validation. This type of testing will best be done on simple topologies, producing required flow interactions on a subset of a full configuration to allow for an accurate representation of the geometrical details as well as the physics of flow interactions. Moreover, extensive instrumentation for high fidelity, on and off the surface measurements can be used in such flows. As the physical understanding grows, more and more flow interactions can be included in a given test. Examples of the type of flow interactions

for which detailed and accurate data are required at appropriate flow conditions include vortical flow interactions, juncture flows, massively separated flow, wing/control surface interactions, flow control effector interactions, etc. Many of these interactions are inherently unsteady.

An important requirement for accurate code validation data is the characterization of the wind tunnel flow in the test section. In wind tunnels, free stream disturbances can affect the physical phenomena being studied. Saric and Reshotko [52] and Owen [53] give guidelines on acceptable levels of free stream disturbances in wind tunnels at different free stream speeds when flow phenomena such as transition, local flow separation, etc. are important issues in data acquisition. In addition, global wind tunnel calibration data must also be available over the entire operating envelope of the facility, and must be shown repeatable at all times between calibrations. Hemsch [54] has outlined an excellent plan for data quality assurance for NASA Langley wind tunnels.

6 Summary

Future challenges in aerodynamics lie primarily in the development of revolutionary and unconventional vehicle concepts that will meet the ever increasing demand for capacity, safety, environmental compatibility, and economic viability. Crucial to such concepts is the development and multidisciplinary integration of innovative flow and noise control technologies. Development of micro- and nano-sensor and actuator technology will be necessary to enable the successful development of adaptive flow and noise control concepts. In addition, highly accurate, reliable, and efficient computational tools are required that can predict turbulent, separated flow at flight Reynolds numbers, with the ultimate goal of being able to certify new technologies and concepts by analysis alone. Development of these technologies and tools hinges on our ability to understand, model, and control complex, three-dimensional, unsteady viscous flows across the speed range. As progress is made towards using computational tools in predicting absolute aerodynamic performance and certifying new technologies and concepts, the role of the wind tunnel should evolve more towards phenomena-based testing and development of code validation databases.

Revolutionary aerodynamics technologies, resulting from significant breakthroughs in our understanding, prediction, and control of unsteady complex flows, will enable a new generation of aerospace vehicles to meet

the societal needs of the 21st Century. New investments in aerodynamics research will be key to this renaissance.

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