AIAA

AIAA 2003-3785

Aerodynamics for Revolutionary Air Vehicles

William L. Sellers III, Bart A. Singer, and Laurence D. Leavitt
NASA Langley Research Center
Hampton, VA

21st Applied Aerodynamics Conference
23-26 June, 2003
Orlando, FL

Aerodynamics for Revolutionary Air Vehicles

William L. Sellers III*, Bart A. Singer†, and Laurence D. Leavitt§
NASA Langley Research Center
Hampton, VA 23681-219

Abstract

Aeronautics research has seriously declined partly because of the perception that it is a mature science and only incremental improvements are possible. Recent aeronautics roadmapping activities at NASA Langley paint a different picture of the future. Breakthroughs are still felt to be possible if we expand the current design space of today's vehicles and optimize the airspace and vehicles as a system. The paper describes some of the challenges that the aircraft and airline industry face. These challenges include political, technical and environmental issues. Examples of the opportunities and technologies that could provide a different vision for the future are discussed.

Nomenclature

b	Span (inches)
C_L	3-D Wing lift coefficient
D	Drag Force
L	Lift Force
M	Mach number
W	Weight

Abbreviations

FLOPS	Floating-point operations per second
MIPS	Millions of Instructions per second
SFC	Specific fuel consumption
CMOS	Complementary metal-oxide semiconductor
LINPACK	Linear algebra software package

Superscripts

'	Fluctuating component

Subscripts

max	Maximum value during actuator blowing cycle
mean	Mean value
min	Minimum value during actuator suction cycle
rms	Root-mean-square value
∞	Freestream

*Head, Flow Physics and Control Branch, Associate Fellow
†Asst. Head, Computational Modeling and Simulation Branch, Senior Member
§Head, Configuration Aerodynamics Branch, Associate Fellow

Introduction

Projecting visions for the future is always a risky endeavor. The tendency in predicting future technological advances is to be overly optimistic in terms of evolutionary improvements, and to be completely blindsided by truly revolutionary advances. These tendencies should not be overly surprising; linear extrapolations of current trends are natural. Foreseeing the nonlinear saturation of those trends is more difficult. Identifying promising opportunities that have real potential for completely disrupting the way we live and work is even more difficult. In the area of aerodynamics and air transportation learned scientists predicted that we would never fly, never cross a speed barrier, or the public would never accept air transportation only to be proven wrong in a relatively short period of time. Those making the negative predictions often worked long and hard on what they believed to be the relevant problems before deciding that no solution was in sight. Their error was in not appreciating that some new approach could bypass the problem(s), they understood to be in the critical path. It is with this in mind that this paper presents visions of a possible future and the impact aerodynamics must have to enable a future filled with new and revolutionary air vehicles.

There is an oft-spoken concern that aeronautics, and aerodynamics in particular, is mature, and nothing more than incremental gains in performance and capacity are possible. That perception is partly due to past successes in the field. The public, for the most part, sees an efficient and safe air transportation system with flights to most every part of the globe. Today's aircraft are a marvel of engineering, science, and technology. Aerodynamic efficiency in terms of ML/D has increased approximately 30% since the beginning of the jet age[1]. Range has increased such that non-stop flights of 8,000 nm are a reality. Aircraft noise has been reduced significantly in the last 20 years.

Unquestionably, the rates of improvement in these areas have slowed, and linear extrapolation of the current rates of improvement could certainly lead someone to conclude that the future holds only incremental improvements. This is especially unfortunate because straightforward extrapolation suggests that significant problems lie ahead. These problems require a rethinking of our air transportation and vehicle systems. The airline industry is under economic pressure and increased public attention to quality-of-life issues, such as noise and emissions will make profits harder to generate and operations more difficult. Prior to September 11, 2001, travelers were facing increased transportation delays and projected growth that would make the situation worse. Geopolitical and economic circumstances have complicated projected growth scenarios, but most projections suggest that air transportation growth will pick up and we again will be faced with increasing delays in a few years.

Hence, just at a time when dramatic leaps in performance would be most beneficial, we are faced with a possible future of slow incremental advances in traditional aeronautics metrics. No one should be blamed for such dire forecasts; they are the predictable result of extrapolating current trends. We can ensure that the forecasts are true by continuing on our current path. We can continue the steady declines in Aeronautics research funding, the steady aging of the workforce in the field, and the inclination to continue to work on familiar problems in familiar ways.

On the other hand, we recognize that huge improvements are possible if we ask the right questions. For instance, we don't need to increase aircraft speed to reduce passenger travel time. We might accomplish this better if we started to look more closely at improving our ability to take off and land safely in a wider range of weather conditions, to take off and land quietly and safely from an increased number of airports, many with considerably shorter runways, and to make air transport accessible to small communities without introducing noise and emissions concerns. While the current hub and spoke system of air transportation evolved as a cost-effective optimum for a given type of aircraft, we have only begun to consider the aerodynamic issues that need to be tackled to provide opportunities for other approaches to air transportation.

The Europeans, to their credit, have formulated a vision for their future in aeronautics, and have a highly effective European framework[2] for research and technology development as well. Perhaps the best example of their vision for the future[3] describes a 2020 future where European aeronautics is the best in the world, and they are winning more than 50% of the world market share in aircraft. The document includes their goals on reduced emissions and noise, and increased air transport safety.

With these factors as a backdrop, in 2001 NASA formulated a team to develop a future vision for Aeronautics. NASA Langley Research Center further refined the vision and started developing roadmaps for technologies to support the Aeronautics Blueprint. Teams from structures and materials, flight systems, controls, and aerodynamics and acoustics looked at their own disciplines and the interactions between them that would be required. The NASA teams' efforts paint an entirely different picture of aeronautics, one in which it is not mature, but is poised to take off in bold new directions.

This paper will focus on the role of aerodynamics in that future vision and discuss the environment and constraints in which it will have to operate. There is a deep belief that for this vision to become a reality, multi-disciplinary efforts must be increased and the interactions dramatically improved. This is especially true if one believes that truly disruptive capabilities can occur through the innovative integration of existing technologies as well as through the invention of new previously undiscovered technologies. Therefore, there will also be a discussion of some of the advancements coming from other disciplines that are critical.

NASA Blueprint for Aeronautics

NASA recently published its blueprint for aeronautics[4] that provides a glimpse of what the future of aviation could be in the year 2050. Revolutionary new air vehicles will be required for this new vision. This new future brings about the possibility for new large, long haul concepts, increased speed, autonomous operations, and the necessity for new vehicle concepts that provide runway independence. The concept of runway independence will require lightweight vehicles with high thrust-to-weight ratio, and very effective high-lift or propulsive systems that will likely have to be low noise solutions as well. The blueprint for aeronautics briefly described some of the new technologies that will enable the increased capabilities of these revolutionary air vehicles.

The blueprint addressed the challenges facing the current aviation system including capacity, safety, and security. It highlighted the fact that there are over 800 restrictions worldwide on aircraft operations that severely limit growth into certain markets. It discussed the issues of CO_2 and NO_X emissions on both air transportation capacity and the environment. It outlined the importance of aeronautics to the future of our nation and the global economy. The blueprint laid out the role of the U.S. government in this future vision. It also stated that NASA's role was to provide enabling technology, by conducting high-risk research, developing unique facilities, and fostering an educated and innovative workforce.

The NASA aeronautics blueprint recognized that if we were to meet these challenges, exciting technologies could open up a new world of aviation. It was proposed that by utilizing the nearly 5,300 smaller airports in the United States, the congestion at the big national hub airports would be relieved, and a new era of point-to-point travel enabled. But as we expand to all those new airports, emissions and noise will become even more critical as a larger portion of our population becomes exposed to these issues due to increased proximity. We will need to learn to operate from shorter runways with less ground-control dependence, and less dependence on ground-based maintenance.

NASA Langley Aerodynamics Roadmap Planning

The Langley Aerodynamics Roadmap Planning Team consisted of representatives from aerodynamics, fluid mechanics, acoustics, systems analysis, NASA program offices, and representation from structures and materials and flight systems and controls. It also included a representative from academia to address future educational issues as well as conceptual design.

Shortly after the planning process began NASA had a change in administration, and a new vision and mission statement.

The **NASA Vision** is:

- To improve life here,
- To extend life there,
- To find life beyond

The **NASA Mission** is:

- To understand and protect our home planet
- To explore the universe and search for life
- To inspire the next generation of explorers ... As only NASA can

The role of aeronautics in the NASA vision is clearly, "To improve life here." In terms of the NASA mission, aeronautics is crucial to understanding and protecting our home planet. These inspirational words are consistent with the NASA Aeronautics Blueprint theme of bringing a new environmentally sensitive level of personal freedom of mobility to the American public.

Technology Issues and Possibilities

Looking toward the future in aerodynamics, the roadmap exercise at NASA Langley saw several general trends. It should be no surprise that multi-disciplinary analysis (MDA) and optimization (MDO) was deemed critical for the future. MDO would have to be expanded to include multi-fidelity methods, emissions and noise constraints, and atmospheric modeling.

What is different is that we see a paradigm shift in the field of aerodynamics from the steady to the unsteady world, and from the linear to nonlinear phenomena. This shift is being brought about by a desire to predict the full flight envelope, which inherently includes unsteady separated flows, and the opportunities to alter the design space using active flow control and structural morphing technologies. The structural morphing can include both small local and large global shape changes coupled with flow control. In fact, in the future we may be able to exploit structural flexibility instead of trying to avoid it. As historically been the case, vehicle designers will continue to exploit technology advances across all disciplines to break through the barriers for innovative approaches for air travel.

These sorts of changes require entirely new ways to think about aerodynamics and how it fits into the broader field of aeronautics. Vast new regions of design space become available when we step towards designing for both unsteadiness and flexibility, rather than against it. How to best use the additional design space is a question that only innovative future research can answer.

In this section, we first look more closely at the aviation system as a system of systems. After appreciating the many levels of interconnectedness associated with aviation systems, we will look in detail at noise and emissions, two particularly important environmental issues that fall well within the NASA mission of "improving life here" and the vision of "understanding and protecting our planet". Next, we will discuss some rapid developments in supporting technologies, which give us hope that the challenges before us can be met.

System of Systems

The NASA Aeronautics Blueprint recognized that the aviation system is in fact a "system of systems". As the demand for capacity goes up, adding additional aircraft to the existing system will in most cases exasperate the problems. Additional aircraft in the sky and on the runways will make the airspace and traffic control issues worse. Adding more airports will bump up against environmental constraints. It was clear that new technology, including new models for the airspace system (vehicles included) needed to be developed so that a systems analysis approach could be taken.

Other teams at Langley have looked at these issues and see a future as depicted in Fig. 1. Today the state-of-the-art is a hub and spoke air traffic system populated with long haul and regional aircraft. The future will include revolutionary air vehicles with exciting new operating capabilities in a fully integrated airspace. In the past we have worked the vehicle and airspace capability axes separately. To achieve the future state, however, we must work them both together, while still mindful that the resulting systems must pass through the additional "hoops" relating to safety/security, environment, and cost.

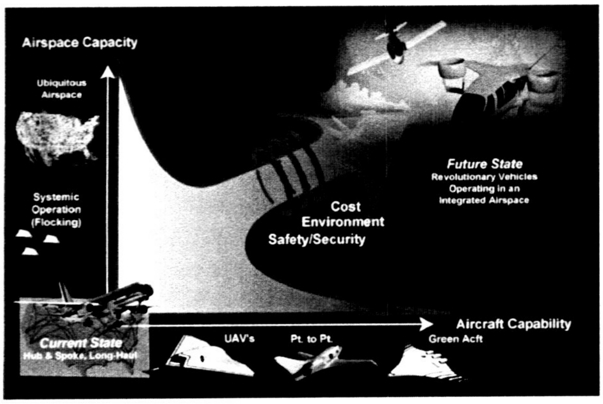


Fig. 1 Strategy for integrated advances in airspace and aircraft

Environmental Impacts of Aviation

Environmental issues are important to the quality of life of the American public. Aviation has the potential for being environmentally detrimental due to the introduction of objectionable noise, and the emission of harmful compounds into the atmosphere. However, an aviation future does not have to be coupled with these environmental hazards. Appropriate and timely research into critical technologies can help us develop an environmentally friendly aviation future. In the following section a short summary of some of the critical issues regarding the noise and emissions impacts of aviation are discussed.

Noise

For the foreseeable future airplanes will create noise, probably at levels that are unacceptably high to those in the immediate vicinity. Long-term exposure to high noise levels poses serious health risks to those exposed. Abey-Wickrama et al[5] document the harmful effects on health resulting from exposure to aircraft noise, while Meecham and Shaw[6] claim increases in mortality rate from studies at Heathrow and Los Angeles. Noise pollution is not just an annoyance, but also a serious health risk.

Unlike many other pollutants, noise actually dissipates (as opposed to just diffusing) with distance from its source. Therefore, a noise-management plan that includes aircraft noise-source reduction, flight-trajectory planning, and community land use around airports can go a long way towards alleviating the health hazards associated with aircraft noise. To be most effective, all aspects need to be worked together as a flexible and dynamic approach. Different aircraft types may have their trajectories optimized for low noise in different ways than other airplanes. Considering such variability in today's airport flight control paradigm is probably unimaginable, but potential future benefits to such a flexible system should warrant at least thinking about such a system

NASA has had a long and successful history of aircraft noise reduction research[7]. The majority of the noise reduction has come as a result of decreased engine noise. This large decrease in noise has been largely a fortuitous consequence of the changeover to high-bypass ratio engines with improved propulsive efficiency and lower fuel consumption. The enormity of the sideline noise reduction associated with reduced engine noise can be seen in Fig. 2. As the engine noise has been reduced, other noise contributors, such as those associated with the airframe become increasingly important. Each new increment of noise reduction gets progressively harder to achieve.

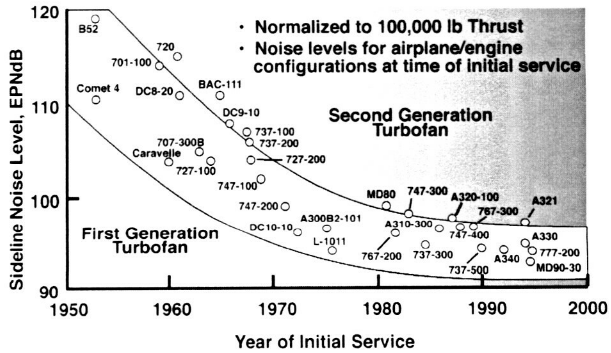


Fig. 2 Progress in noise reduction research

The Noise Reduction Element of the NASA Advanced Subsonic Transport (AST) program that ended in 2001 had a goal of developing technologies for a 5dB noise reduction. Even if all the technologies developed in the AST program were to find themselves on the next airplanes rolling off the production lines, the slow rate of replacement of aircraft coupled with projected increases in passenger and cargo operations, make even maintaining the noise impact at constant levels a short-term achievement at best. The current NASA noise initiative has a goal of reducing noise, relative to a 1997 baseline, by a factor of 2 in 10 years and by a factor of 4 within 25 years. A factor of 4 reduction corresponds to a 99% reduction in sound power. As described in reference 7, these reductions would not make the aircraft inaudible, but would contain the noise impact within most airport boundaries. To meet these goals, both propulsion noise and airframe system noise will need to be reduced by similar amounts. To contain the noise impact within the airport boundaries of all the major airports will likely require an even greater reduction. The goal of reducing perceived noise by a factor of 4 in 25 years may require totally new aircraft systems[7,8] that incorporate noise shielding and/or other technologies that must be built into the conceptual design of the aircraft and not simply handled as a retrofit.

The impact of noise will become increasingly important as a result of the increased freedom of mobility. Containing the noise impact was based on keeping the day-night average sound level (DNL) 55dB contour within the airport boundaries. The team recognized that there is a difference between noise regulations and community acceptance and putting more small aircraft into the 5,300 public use airports may require even more improvements in noise reduction. Military operations are coming under more scrutiny as well. As base consolidations are progressing and additional air wings are stationed at fewer bases in the U.S., the military is being urged to more seriously consider the environmental noise impacts of basing.

Emissions

There have been numerous recent studies[9,10,11,12,13] of the impacts of aviation on the global environment. The NASA Blueprint highlighted some of the issues regarding carbon dioxide (CO_2) and nitric oxide (NO_X) emissions. The production of CO_2 can be directly related to fuel burn, whereas the production of NO_X is related to combustion efficiency. A discussion of the atmospheric impact of emissions and the potential technologies to reduce them is discussed below.

An excellent summary of the main constituents and their effect on climate changes from aviation was provided in reference 10. Their estimates were based on the assumption that passenger traffic was projected to grow by 5% annually from 1990 to 2015, and total aviation fuel use by 3% per year during the same period. After 2015 projections were so uncertain that they established a reference and several other possible emission scenarios due to different aviation constraints.

The primary emissions include the greenhouse gases CO_2 and water vapor (H_2O), and other major emissions including NO_X, sulfur oxides (SO_X) and soot. Aircraft emissions further alter the atmospheric greenhouse gases, CO_2, ozone (O_3) and methane (CH_4). In 2050 the increase in CO_2 from aviation, based on the various scenarios, is expected to range from 1.6 to 10 times the amount in 1992. The increase in ozone by NO_X emissions in the mid-latitudes is expected to increase by 13% in 2050. Most water vapor emissions are rapidly removed by precipitation, however emissions in the lower stratosphere can build up to larger concentrations. Since water vapor is a greenhouse gas this buildup would tend to warm the Earth.

Contrails from aircraft were not mentioned in the NASA Aeronautics Blueprint because at the time, the impact of contrails on climate change was uncertain. Contrails tend to warm the earth and there was conjecture that they could spread or diffuse into thin high clouds. The full impact was difficult to assess[14] because they spread into non-linear, natural-looking cirrus clouds. It was especially difficult because the dense air traffic prevented the analysis of isolated contrails. There were hints, however, regarding the impact. Satellite imagery of a racetrack contrail pattern generated by a NASA DC-8 test aircraft off the coast of California, showed that it later formed a 60-mile cloud system over the state.

The unprecedented shutdown of aviation traffic due to the 9/11 disaster provided a rare opportunity to look at contrail spreading[15]. The only aircraft flying during that period were a few military aircraft that generated isolated contrails in areas that typically were crossed by 70-80 planes an hour. Six aircraft were responsible for the formation of cirrus clouds that covered more than 20,000 km^2 in an area between Virginia and Pennsylvania[16]. This allowed Minnis et al[15] to conduct a detailed analysis of the isolated contrails and to develop models to simulate both the contrails and their spread to cirrus clouds.

Technologies to reduce Emissions

There have been several European studies[1,17] predicting the potential for a 50% reduction in fuel burn over the next 20 years. Accounting for this reduction among various disciplines can always be debated because of the variety of ways design trades can be accomplished. Fig. 3 shows that the authors predict that 36% will come from aerodynamics technologies (e.g. lift and drag), 23% from engine technologies, and 8% from structural systems (e.g. weight reductions).

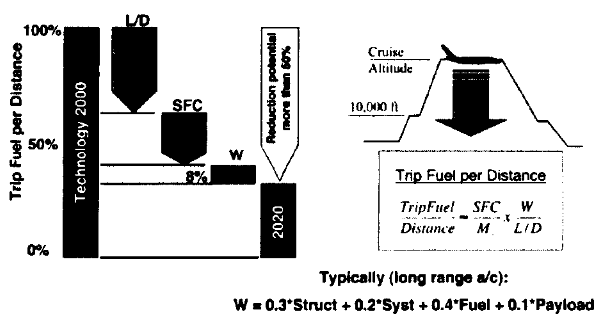


Fig. 3 Potential for fuel consumption over the next 20 years (from Ref. 1)

To obtain these results, the authors of reference 1, used a simplified form of the range equation and a breakdown of the weight buildup of a typical long-range aircraft to show that improvements in L/D and SFC have an order 1 effect, while structural weight improvements will be less important. Drag is critical to fuel burn and the Europeans are attacking drag in any form including friction, wave, and induced drag. Aerodynamic technologies that they considered include both laminar and turbulent flow management. This includes laminarizing the wing, tail, and nacelles using hybrid laminar flow control (HLFC) to reduce friction drag by 22.5%. Variable camber and smart wings are projected to provide a 10.5% reduction in drag by optimizing the L/D throughout the flight envelope as well as increasing the buffet boundary. Shock boundary/layer control is projected to provide another 3.0% reduction in drag. Schneider[1] provides an interesting statistic that helps to relate these improvements back to emissions. He estimates that a 1% reduction in aerodynamic drag for a long-range aircraft results in a savings of 400,000 liters of fuel per year and aircraft, which in turn will save approximately 5,000 kg of noxious emissions.

Pursuing L/D and SFC improvements without considering the vehicle, airspace, and atmosphere as a system can lead to bad results. Green[11] presents a summary of a report that investigated the challenges of reducing emissions. The approach was more conservative in their technology estimates than the IPCC Report of reference 10, in that only nearer term market driven technologies were considered. They developed models for emission products, aircraft missions including vehicle characteristics and operating parameters. The study identified that current market trends for large, long-range aircraft, with reduced operating costs through reduced fuel burn, "will or may, increase the impact of air travel on climate change." Their results showed the current long-range wide-body scenarios (e.g. 13,000 km to 16,000 km range) were inferior to vehicles designed to operate at stage lengths of 5,000 km or less. For the same payload, the long-range aircraft is substantially heavier than one designed for the shorter range. They recommended a full system study of long-range travel in stages of 7,500 km or less be initiated. They also found that the current trend of increasing engine pressure ratios to improve thermal efficiency might increase NO_X emissions. The modeling of the greenhouse effect with altitude suggested that cruising at lower altitudes might reduce the climatic impact. All of their findings have potentially large impacts on the optimization of commercially viable aircraft and additional research is required into both the technologies and the system analysis benefits.

Rapid Developments in Supporting Technology

Other discipline technologies are critical to the future vision, since many of the new vehicle concepts will incorporate active flow control, autonomous flight capability, and highly integrated airframe/propulsion systems, and smart structures and materials. A brief discussion of these technologies and the assumptions that affect our future vision is included in this section.

Computational Speed and Processing Power

Information technology, computational speed, and processing power will be critical to future aerodynamic developments, both in the way we analyze flows, and the ways we implement or control the new aerodynamic technology. Gordon Moore, a co-founder of Intel, made a prediction in 1965 that the number of transistors on a silicon chip would double every 24 months. His "law" in the beginning was more an economic observation more than a technology fact. Progress however, has been extremely rapid. In the early days it took 3 years to move processing speed from 25 to 50 MHz, where today Intel adds 25 MHz every week, and in the next two years the industry expect to do that in day[18]. Moore's law is not leveling off and Fig. 4 shows a projection of transistor density through 2010. The industry projection is that by 2007 there will be one billion transistors on a chip.

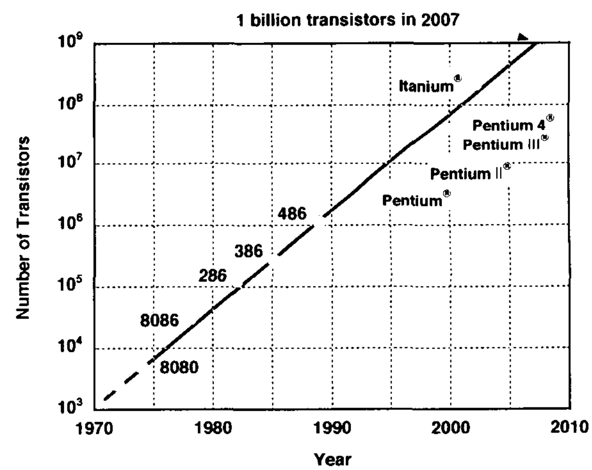


Fig. 4 Projection of Moore's Law for transistor density

Gelsinger in Reference 18 states: "knowledgeable people have questioned Moore's law for a long time. Apparently they are daunted by the same stifling factors that have always impeded innovation and development. They cite physical size limitations, runaway power consumption, and prohibitive costs as being insurmountable barriers. ... As far back as 20 years ago, people doubted that the progress would continue and many barriers (e.g. 1-micron) were professed to be impossible only to be broken as new processes were developed". Intel labs recently announced[19] the development of new "TeraHertz" transistors that will extend Moore's law for decades. In the development process Intel had to address many of the barrier issues that people were saying could not be broken. When transistors are scaled down power consumption rises exponentially, and current leaking through the gate dielectric and from the transistor source to the drain when power is off drives this rise. To increase speed requires thinner dielectrics that many people said couldn't be made because they would only be a few atoms thick. As a tradeoff, they had to consider that thinner dielectrics also leak more. Each one of these problems was attacked using new architectures, new materials, and nanotechnology. In fact, Bob Gasser of Intel states[20]: "that nanotechnology is here today in the state-of-the-art high speed Silicon CMOS process technologies". They are already using self-assembly molecular manufacturing forming the dielectric one atomic layer at a time. Intel states that in the last three years they have manufactured and sold over 50 quadrillion nano-transistors. Their projections for CPU speed and density is that 10 GHz to 100 GHz processors are not fantasy and in fact the new multi-billion transistor processors will allow you to reach current supercomputer capability with 5 or fewer of these chips.

How we use such incredible capability will lead to some exciting possibilities. The increased processing speed and chip density provides two areas of immediate application in regards to advanced aerodynamics analysis and revolutionary vehicles. Artificial intelligence and autonomous operation of flight vehicles will be an enabling technology for several classes of flight vehicles (e.g. Personal Air Vehicle). It will also allow the distribution of control necessary for new architectures for the airspace system itself.

Artificial Intelligence

There are several research groups that project an exponential growth of knowledge in the next 20 to 30 years. They argue that the exponential growth itself makes future projections difficult because it is felt that one cannot even imagine the possibilities that await at the "Spike" or discontinuity resulting from exponential growth or accelerated knowledge.

Moravec[21] in the field of artificial intelligence and robotics, projects increases in computational speed and reduced cost will provide enough processing power to match the human brain by 2020. He shows in Fig. 5, the evolution of computing power versus cost, and its impact toward mimicking various biological organisms. He bases his comparison on the number of neurons in each organism and provides the rationale for the criteria as a means of comparison. He traces the evolution of computing power from the 1900's (prior to current silicon devices) and projects the growth forward. What he and others[22] have found is that the long-term evolution has not been one single path of progression; rather it is a series of "S-curves" that trace the progression of individual technologies. The impact on revolutionary vehicles will be distributed processing and control that will enable autonomous operation, distributed flow control, and entirely new paradigms in airspace management because airspace control can be distributed between the vehicles and the ground. With distributed sensors integrated vehicle health monitoring will become a reality and offer new levels of safety and security.

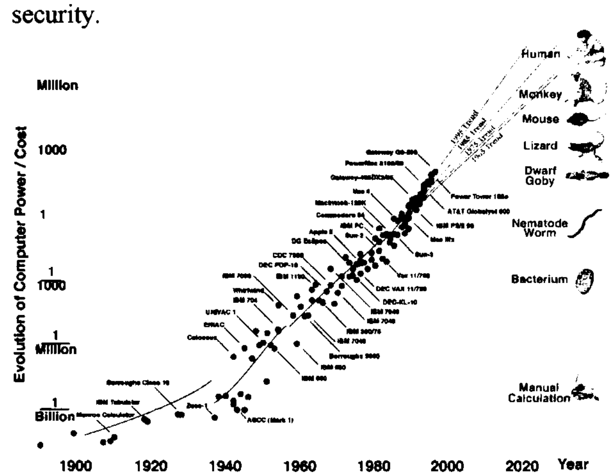


Fig. 5 Comparison of computing versus brain power (from Ref. 21)

For aerodynamic predictions raw processing speed may be a better indicator of the future rather than the MIPS/$1,000 criteria used by Moravec for robotic applications. Dongerra[23] has been tracking the processing speed of computers ranging from the Apple II to Supercomputers using the LINPACK benchmark. Over the years the tracking has expanded to cover the change from vector to parallel machines, and the results have also been organized and placed on a dedicated website[24] ranking the top 500 supercomputers in the world. Fig. 6 shows results from that site that indicate that in terms of raw processing capability, supercomputers are doubling every 18 months, and will reach Petaflop (10^{15} floating point operations per second) speed by the year 2010.

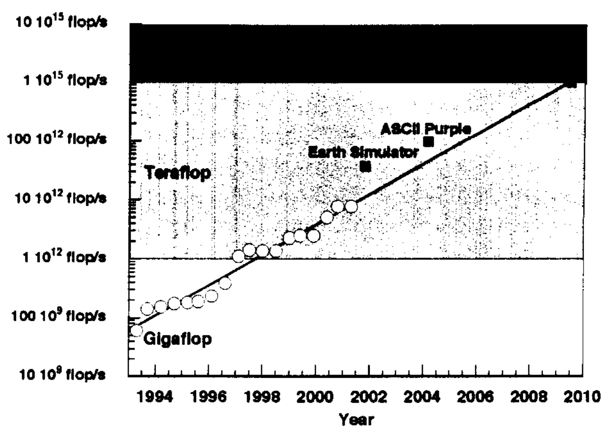


Fig. 6 Projected increase in supercomputer processing power based on LINPACK benchmark

There are also new trends that show that PC clusters are now present at all levels of performance, and 2 new PC clusters have made it into the top 10. To even be considered to be in the top 10 category requires a computational speed of 3.2 Teraflop. The result of all the increased computational power[23] is that a computation that in 1980 took a full year to complete can today be done in approximately 5 seconds.

Emerging Aerodynamics Technologies

A detailed discussion of the emerging technologies would be difficult in this paper due to the dramatic increases in applications and technologies. In this section the reader is pointed to recent review articles. By highlighting selected technologies we hope to set the foundation for understanding that major change is possible. Many of the technologies are not "imagination", but moving rapidly through the development process. The maturation time will only shrink as new computing and information technology becomes available.

It was also recognized that significant improvements toward the final vision goals could be made without resorting to advanced technology. Liebeck[25] in his Wright Brothers' Memorial Lecture described the evolution of the design of the blended-wing-body (BWB) concept. The BWB provides a 19% reduction in operating empty weight and a 32% reduction in fuel burn compared to an advanced long-range transport concept. It achieves these benefits based on the configuration design and vehicle layout and does not resort to advanced materials, structures, or aerodynamics. As Liebeck states: "Once-apparent show-stoppers have been reduced to technical challenges, or in most cases proper solutions". The roadmap planning team felt that to make more vehicles like the BWB, which are a departure from our current design space, will require significant improvements in our conceptual design tools and capability. Since these new designs are significant extrapolations from current vehicles, validation of the experimental and computational design tools is critical for the future vision. McMasters et al [26] and Dreisbach[27] provide an industry perspective toward the issue facing airplane design including the training of the next generation of design engineers. In this section we discuss the vehicle classes considered and some examples of the emerging technologies including active flow and noise control, smart adaptive structures, and improved conceptual design methodology.

Vehicle Classes

Determining the suite of technologies that will play a critical role in the future vision is complicated by the large number of possible vehicle classes. The critical requirements for each of these vehicles do not form a self-consistent set because the highest priority technology for one vehicle class may not be the critical technology for another vehicle.

The approach taken to identify candidate technologies during the roadmap planning exercise at NASA Langley was to look across a wide spectrum of vehicle classes. In the transportation sectors these include Personal Air Vehicles (PAV), general aviation (GA), business jets, regional and long haul aircraft. In the military, sector these include Uninhabited Air Vehicles (UAV) and high-performance vehicles. The vehicle sectors considered were narrowed down to PAVs, a quiet, green transport, and a supersonic overland vehicle. It was felt that the enabling technologies for these three vehicles would cover most of the requirements of the other classes.

Background research was undertaken to identify past studies relevant to each of these vehicle classes. The National Research Council (NRC) has published several studies over the years of supersonic vehicle capabilities. One recent study[28] by the NRC evaluated commercial supersonic technology and they described barrier issues relating to vehicle performance and environmental impact. Advances in aerodynamic performance will be required to make a supersonic vehicle commercially viable and their outlook was based on whether the vehicle mission was a Mach 1.6 business jet or a Mach 2.4 High Speed Civil Transport (HSCT). In the case of the business jet the study identified a need for a 10% improvement in L/D, air vehicle empty weight fraction, specific fuel consumption, and thrust to weight. In the case of the HSCT, a 15% improvement in all the above categories was required and reaching that goal was deemed to be beyond the 25-year horizon. The environmental barriers are significant and require either elimination, or reduction to acceptable levels the sonic boom for overland flight. The vehicle also has to demonstrate a benign effect on climate and atmospheric ozone. The quiet green transport has the environmental noise and emissions barriers discussed in detail earlier. There are a variety of technologies that can be brought to bear ranging from active flow and noise control to smart structures and materials.

Looking across vehicle classes and the background literature revealed technologies that can significantly improve L/D, reduce noise, and provide the tools for advanced vehicle conceptual design. The team felt that a concerted effort to reduce drag in all its forms was of particular importance because reductions in fuel burn through reduced drag results directly in reductions of CO_2 and water vapor emissions. Fully utilizing the more than 5,000 smaller airports presented serious noise issues and the development of technologies for predicting and controlling noise was considered critical.

Flow and Noise Control

Passive and active flow and noise control has seen a resurgence of interest in the last decade, as a result of either correcting vehicle problems or expanding the design space due to new vehicle constraints. In the following discussion, we will use the delineation of active versus passive flow control proposed by Gad el Hak[29], which is based on whether energy is expended to achieve flow control. The field of flow control is so broad that it is beyond the scope of this paper to describe all the work being pursued. Kumar et al [30], and Thomas et al[31] provide excellent reviews of some of the issues and future directions of these exciting technologies for vehicles, and Lord et al[32] give similar information for gas turbine engines. In this paper, samples of technologies being developed around the world that illustrate how one may address the critical issues (e.g. fuel burn, L/D, drag reduction) will be presented. Reducing fuel burn in many cases means reducing drag in all its forms. The typical drag buildup for aircraft is shown in Fig. 7.

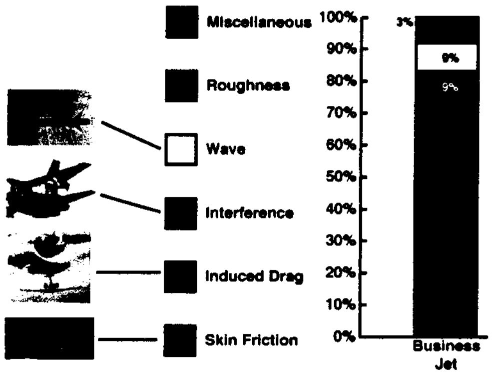


Fig. 7 Typical breakdown of drag components

Skin friction and induced drag comprise almost 70% of the total drag of a vehicle. Wave drag is a substantial portion of the drag and varies from one vehicle type to another.

Passive Flow Control

Passive flow control technology has been worked for more than 50 years and shown to be applicable to a wide range of issues including separation control, secondary flow control in inlets, and most recently transition or laminar flow control. Lin[33,34] has reviewed the field of passive flow control using micro vortex generators (MVGs) or micro vanes. Vortex generators have used for many years in the field of separation control. The MVG concept came from many years of research into separation control technology and the resulting fundamental question regarding how small can the devices be and still be effective. Lin evaluated numerous devices and found that a small vane type generator extending only 20% of the boundary layer height is still effective. When these devices are applied to a high-lift system they provide both operational and separation control benefits. Operationally they were small enough that when the flaps retract they can be stowed in the flap cove and thereby avoid a cruise drag penalty. In terms of separation control, when applied to a modern multi-element high-lift system they provided an L/D improvement of 100%, and a lift increase of 10%. These devices have been used successfully on the Piper Malibu Meridian aircraft and are used on the Gulfstream V aircraft for shock separation control. Lin in reference 34, provides many other examples and applications of passive flow control technology using MVGs and micro-vanes.

The use of longitudinal grooves on the surface of the skin or "Riblets" is probably the best-known passive drag reduction concept for a turbulent boundary layer. Riblets have been studied, both in the U.S. by Walsh[35] and others in Europe, for over 15 years. They were developed at NASA Langley in the early 1980's as part of a broad research effort in viscous drag reduction that also included large eddy breakup (LEBU) devices. NASA teamed with the 3M Corporation to produce a thin Mylar film that had the proper Riblet geometry and spacing embedded into the film. Of all the concepts considered at NASA, Riblet technology is the only turbulent drag reduction concept to make it to flight demonstrations[36,37,38]. At NASA Langley it was flown on a Learjet where it confirmed that turbulent skin friction reductions of 6% were possible in flight. The Europeans have continued to pursue Riblet technology and conducted film durability evaluations[38,39] on a Lufthansa Airbus A300-600 aircraft between 1988 and 1990. The testing involved placing samples at various locations on the aircraft to evaluate effects of operating temperatures, film erosion, ultraviolet rays, and fluid spills on the Riblet film. It was reported that there was no serious damage to the film except in high erosion areas and those areas exposed to anti-icing fluid. Marec[40] describes a flight demonstration done in 1988, conducted by Daimler Chrysler Aerospace Airbus, with Airbus partners, 3M France, and ONERA. In this demonstration they covered 700 m^2 of an A320 with Riblet films and measured a reduction of 1 to 1.5% in fuel burn. The Europeans are continuing operational testing of the Riblet films on a Cathy Pacific Airline A340 aircraft. Operational testing demonstrated[39,41] that the Riblet film remained unclogged and undamaged over an 8-month operational period and that the film did give the expected fuel savings. Marec[40] states that in regards to Riblets and drag reduction: "... much remains to be done in basic research: refined optimization of the shape of riblets, and the use of other concepts to be imagined". One is left to imagine that the removal of the manufacturing constraints of the 80's and 90's and the introduction of new materials and manufacturing processes might provide larger improvements using 3D Riblet geometries. Viswanath[42] provides a recent review of all the Riblet research to date.

The final example of passive flow control technology highlights the research of Saric et al[43] investigating the use of leading-edge roughness as a transition control mechanism. This innovative technique grew from many years of fundamental research into crossflow instabilities and boundary layer receptivity. Crossflow instability is one of the primary transition modes for swept wings typical of a transport aircraft. Saric's research showed that these instabilities are sensitive to 3D roughness near the attachment line of the wing. By placing small 3D roughness elements at various spanwise spacing they could excite various crossflow modes or wavelengths. Choosing the wrong size or spacing can move transition forward and increase drag. Careful placement of small 3D roughness elements to excite a subcritical mode delayed transition by drawing energy from the most unstable mode. In the Arizona State University experiment Saric states: "The most remarkable result obtained from the subcritical roughness spacing is the dramatic affect on transition location ... Use of subcritical roughness spacing delayed transition beyond the pressure minimum and onto the trailing-edge flap at x/c=0.8"

Passive flow control technology is important. In the areas where it is applicable it is an efficient technique, and provides a benchmark against which to compare other methods. The one drawback is that it is a point design and as conditions change in flight the effectiveness of the technique may diminish rapidly. The knowledge gained by understanding the flow physics during the development of passive flow control technology provides a framework from which to investigate active flow control technology, which may adapt to changing conditions and provide even greater benefits.

Active flow control technology

Active flow control technology has generated tremendous interest in the last few years based on experimental and computational results. Many of these technologies are in their embryonic stage and will require many more years of development plus advances in the supporting technologies mentioned earlier. If the benefits they promise materialize their potential payoffs can be quite substantial toward meeting the NASA goals. A few of these concepts have reached a level of maturity that they are undergoing testing that takes into account the relevant operating environment in which they have to operate. This may include confirming the technology works at flight Reynolds numbers or the physical scaling of the systems from the laboratory to flight article integration.

Active flow control technology has a wide range of applications and can typically be divided into two broad categories depending on whether they involve localized fluid interactions or localized shape deformation. In the case of fluidic interactions the recent emphasis has been on small-scale inputs that provide large outputs based on exploiting some type of instability or particular flow sensitivity. Potential applications include: separation control, mixing control, vortex control, circulation control, boundary layer control and shock/boundary layer interactions. Washburn[44] provides an overview of the flow control research underway at NASA Langley. The program spans many of the application areas above and is continually seeking new ideas or approaches.

Laminar Flow Control (LFC) is one technology that has moved from concept to flight demonstration and has a substantial benefit in terms of drag reduction. Laminar flow control is typically active flow control (e.g. suction) that aims to keep a boundary layer from transitioning to much higher Reynolds number than would occur normally. Joslin[45,46] provides a detailed review of the historical development and validation of LFC technology that spans over 60 years of research. He defines the LFC categories that include Natural Laminar Flow (NLF), in which wing shaping is used to discourage the growth of instabilities, and Hybrid Laminar Flow Control (HLFC), which combines active laminar flow control with NLF. Active laminar flow control is rarely used alone and is almost always combined with appropriate wing shaping. In a study by Acara et al[47] that compared an advanced subsonic twinjet with HLFC on 50% of the upper wing, horizontal and vertical tails, and 40% HLFC on the engine nacelles resulted in reductions in TOGW of 10%, OEW of 6%, and block fuel of 15%. Although the technology has been flight evaluated by both the U.S. and European aircraft industry, much still needs to be done. Joslin points out that issues precluding the use of LFC on commercial aircraft today include: resolution of some of the potential performance penalties versus the benefits, demonstration of the reliability, maintainability, and operational characteristics, development of an HLFC compatible ice-protection system, and viable high Reynolds number test techniques. Future concepts for LFC such as Saric's distributed roughness provide alternate ways to control the boundary layer and new technologies will be developed when theoretical and predictive techniques have improved.

Active separation control is another area that is receiving considerable attention. It is of particular interest because separation is so pervasive in fluid flows and can be so detrimental to vehicle or system performance and structural integrity. Greenblatt[48] and Wygnanski provide an excellent summary of the history, applications, and issues associated with active separation control. Washburn[44] describes the collaboration between NASA Langley and researchers at Tel Aviv University (TAU) to move this technology for high lift separation control from the laboratory to flight environment. Leveraging the many years of experience at TAU, the research team has demonstrated that separation control works at flight chord Reynolds numbers (37 million), investigated compressibility effects, mild sweep (with the separation location dictated by the geometry), and oscillatory blowing efficiency. The researchers were able to show that oscillatory blowing is two orders of magnitude more efficient than steady blowing, but that addition of weak steady suction is also very effective. NASA Langley supported a system study[49] of the benefits of active flow control from the Boeing Company. The study identified that simplification of a high lift system (via active flow control) to be the highest priority and payoff. Utilizing a simple hinged flap with a drooped leading edge provided a 3.3% reduction in both drag and weight, and a 2.6% reduction in part count. The study identified additional technology issues such as the need to validate the technology at high flap deflections, and the validation of simultaneous use of leading and trailing edge separation control. NASA Langley is continuing this research effort aimed at a wind tunnel validation of the 3D concept illustrated in Fig. 8. Other active flow control concepts for high lift augmentation are also being pursued at NASA Langley

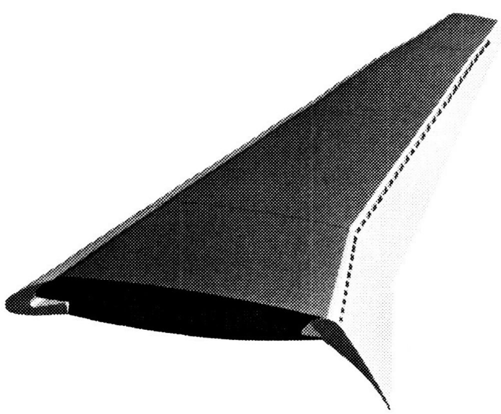


Fig. 8 Three Dimensional (3D) Simplified High-Lift System Concept Using Flow Control

Circulation Control Wings[50] (CCW) have been studied for almost 65 years and the benefits have been highlighted in flight tests that focused on high-lift. Traditionally CCW wings use blowing at the trailing edge and the "Coanda effect" to turn the flow over a curved trailing edge. The blowing generates significant streamline turning that results in super-circulation and high-lift. In spite of the significant improvements in performance, CCW have not been applied due to the systems penalties dealing with engine bleed requirements and cruise performance. As a result of the lessons learned during the separation control research described above, a study was conducted by Jones el al[51] to see if using unsteady pulsed circulation control one could reduce the mass flow requirements, and thereby remove one of the significant roadblocks to the technology. Jones' General Aviation Circulation Control (GACC) airfoil included a novel dual-blowing concept for the trailing edge whereby simultaneous blowing from the upper and lower surface would provide a "virtual trailing edge" to reduce the cruise performance penalty. The results from his investigation have shown the potential for a 48% reduction in mass flow. The dual blowing concept also provides the opportunity to make the entire wing into a distributed control surface. Spanwise variation of the upper and lower surface blowing may provide a distributed or tailored load distribution, pneumatic ailerons and split flaps. This technology is now being investigated for use in a variety of concepts and applications that include pneumatic nacelles for performance efficiency, and maneuvering control. Other studies are looking at other system impacts of circulation control such as noise. Monro et al [52] studied the acoustic characteristics of a CCW and a conventional wing high-lift system. Their results showed a lower noise spectrum for the CCW wing as compared to the conventional wing for the same lift. The authors' point out that even if the noise were comparable, CCW would be an advantage because the CCW wing would be lighter.

The second broad area of active flow control pertains to structural morphing or localized shape changes. Stanewsky[53] provides a comprehensive overview of the adaptive wing technology and flow control technology being considered. European[54] researchers have been pursuing this area very hard and have coined the phrase "adaptronics" to describe the technology.

If the goal were to reduce emission, then technology that will increase L/D or reduce drag would be of particular interest. Kroo[55] reviews current analysis and design methods and provides several examples of design concepts to increase L/D. These concepts include nonplanar systems, multiple surfaces, and wing tip devices. Tip sails are just one of the many wing tip devices reviewed, and Kroo illustrates the benefits by highlighting a simple tip sail consisting of two elements. With this configuration he was able to predict an increase of 11% in span efficiency. He later conducted an experimental investigation of the concept that validated the 10-11% reductions in vortex drag. Kroo also presents an innovative design methodology for nonplanar wings based on a genetic algorithm approach. The wing system had many elements with arbitrary dihedral and twist. The algorithm was allowed to build up several generations of candidate designs of wings that proceeded through the discovery of winglets and ultimately to a C-wing concept with significant induced drag reductions. Boeing later studied the C-wing[56] for application to a very large aircraft.

The European Union (EU) has focused a considerable effort in both L/D improvement and drag reduction. An excellent example is illustrated by the research conducted by the EUROSHOCK I, and II projects. The goal was to reduce drag resulting from shock and boundary layer interactions. Earlier efforts in EUROSHOCK I definitively showed that passive shock control could be ruled out as an effective means of reducing drag on laminar wings. They also ruled out passive techniques for turbulent wings due to the increased sensitivity of the technique to changes in the flow and boundary layer conditions. Those findings lead them to undertake active control techniques in EUROSHOCK II. Stanewsky et al [57] have compiled an extensive summary of the findings of the experimental, computational, and systems analysis efforts undertaken. In a carefully conducted assessment of a variety of available drag reduction techniques, their efforts focused on the development of an adaptive bump on the upper surface of the wing. The bump was the most effective means of drag reduction and had added benefits relating to buffet. The amount of drag reduction obtained varied as expected depending on 2D/3D results, but also varied based on the type of vehicle (regional/long-haul) and whether the wing was designed for laminar or turbulent conditions. Their systems benefits included the weight penalty involved with modification of the wing for the bump. A reduction of fuel burn of 2.11% was achieved for an A340-type long-haul vehicle with an HLFC wing. For a conventional "turbulent" wing with weak shocks at cruise by design, their studies showed that similar benefits could be achieved, but the bump had to be adaptive to account for the large chordwise movement of the shock. Recommendations for future work included: "Consider new wing designs with a bump integrated into the design. This way thicker wings could be built with less structural weight and reduced time for manufacturing ... and providing suitable materials and (smart) structures for such a bump". Stanewsky further describes in Reference 53, how the bump can be coupled to adaptive wing technology to reduce drag, optimize L/D over a wider range of flight conditions, and increase the buffet margins. Computational and experimental prediction methodology is enabling for all these efforts as it moves more into the mainstream of analysis, design, and optimization.

Revolutionary Vehicle Concepts

The Aeroroadmap team felt based on various research efforts that although advanced technology could be retrofitted to existing aircraft, to obtain the most benefits required integrating the technology into the aircraft at the conceptual design phase. Advanced technologies have demonstrated throughout history that they can be used both to overcome old barriers as well as to add new capability.

Revisiting the Past

As mentioned earlier, disruptive innovations can occur through the creative integration of existing technology. A focus on new missions with what appear to be unobtainable (given today's technology levels) performance is one way new design space may be opened. DARPA often utilizes this approach to 'encourage' advances that might otherwise take many years to bring to fruition. In other cases, there is evidence that suggests that revisiting past conceptual designs with the aim of using advanced aerodynamic technologies (e.g. flow control or new CFD design or analysis capability) can remove many of the barriers that prevented the older designs from being successful. There are countless examples of this. The concept of the wing warping for vehicle control dates back well prior to when the Wright Brothers successfully employed it in their first powered flight at Kitty Hawk, North Carolina in 1903. This form of control gave way to ailerons over the years, but made a comeback in 1990 with the Active Aeroelastic Wing program. The AAW flight test vehicle is currently being flown at the Dryden Flight Research Center[58]. The AAW concept utilizes aeroelastic flexibility to deform the thin wing into the optimum shape for the desired performance. Another example, thrust vectoring was apparently conceived in 1909 well before the advent of high thrust to weight ratio gas turbine engines capable of supporting the concept. The F-22 Raptor will be the first conventional take-off and landing production high performance aircraft in the U. S. to utilize thrust vectoring for maneuver, almost 100 years later. Lastly, flying wing concepts such as the Blended Wing Body[25] discussed earlier have been around since the mid to late 1800s. In fact, over 200 vehicles have been flight tested (both powered and unpowered) over this period as discussed by Wood[59], yet we consider the BWB to be a 'revolutionary' new vehicle concept. Even so, Liebeck's BWB design does show at this early stage, significant L/D improvement potential (approximately

15-20%) when compared to the state-of-the-art wing/tube design philosophy currently employed in the transonic transport industry. Even larger improvements might be realized if boundary layer ingesting inlets become practical. In this section the authors will provide examples of "revolutionary" vehicle concepts that had been previously considered and were thought to have significant benefit over conventional configurations, and that we believe may be possible in the near future with advanced technology. These concepts utilize the following technologies: Custer Channel Wing, circulation control wing, strut-bracing for transonic and supersonic speeds, distributed propulsion and tilt nacelles.

Pneumatic Channel Wing

NASA in collaboration with Georgia Tech Research Institute is revisiting the channel wing concept[60,61], to develop very high lift for Extreme STOL (ESTOL) applications, but with a very simple system, that has no externally moving parts. The powered-lift Pneumatic Channel Wing concept combines Circulation Control (CC) aerodynamic and propulsive technologies with the advantages of the Custer Channel Wing to provide a configuration intended to have ESTOL or perhaps even near VSTOL capability, but without the ability to hover. The application of CC to the channel wing solves an important problem of the original channel wing concept. While the channel section was essentially stall-proof, generating increasing lift up to 45 degrees angle of attack, this lift was unusable in takeoff or approach because of limited tail scrape angles of the fuselage (typically about 12 degrees), lack of pilot visibility, and low-speed handling, stability and control issues. The use of CC provides increased channel circulation lift in a large streamtube, at lower, usable angles of attack. A preliminary design study of this pneumatic vehicle is based on previous wind tunnel and flight-test data. Advanced flow control technologies are integrated into a simple Pneumatic Channel Wing (PCW) configuration, shown in Fig. 9. Preliminary wind-tunnel development and evaluations of a PCW powered model have shown substantial lift capabilities for the CCW blown channel wing configuration[62]. C_{LMAX} approaches 8.0 to 9.0 using just the channel portion of the wing, i.e. no outboard blowing. The blown model also showed the ability to interchange thrust and drag by varying blowing to provide greater flexibility in Super STOL takeoffs and landings. Sellers et al[63] discuss adding the outboard CCW w/ pulsed trailing edge pneumatics, which is expected to increase the high lift performance and provide improved flight control capability.

Circulation Control is very attractive for Personal Air Vehicle (PAV) and GA concepts because of their inherent low takeoff and landing speeds. Circulation Control is most effective at lower velocities since the key driving parameter is the jet velocity compared to freestream velocity ratio. Thus, lower takeoff and landing velocities can utilize lower jet velocities or lower mass flows while achieving the same effective lever-arm on the maximum lift.

As described in Reference 63, one of the simplest uses of Circulation Control applies to the GACC airfoil with the utilization of a turbocharger to power the pressurized blown plenum. Since turbocharging is merely used for altitude compensation in GA aircraft, and not increased power at takeoff, all the turbocharger compressed air is dumped out a waste gate at this condition. Thus a no cost air supply is present, with air mass flow on the same order as are required for a moderate performing CC system. The authors' show that Circulation Control could potentially be highly synergistic in several more exotic application areas, including the use of distributed propulsion systems.

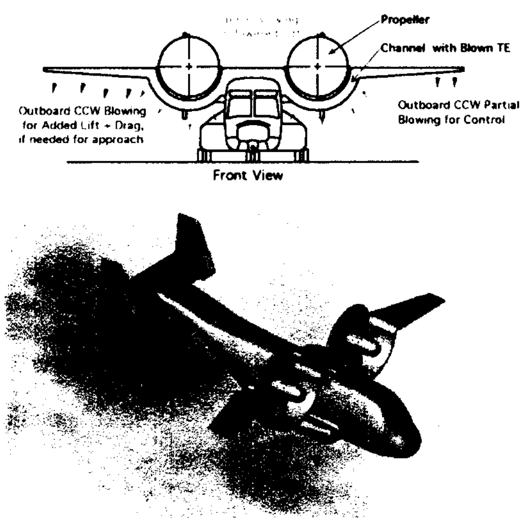


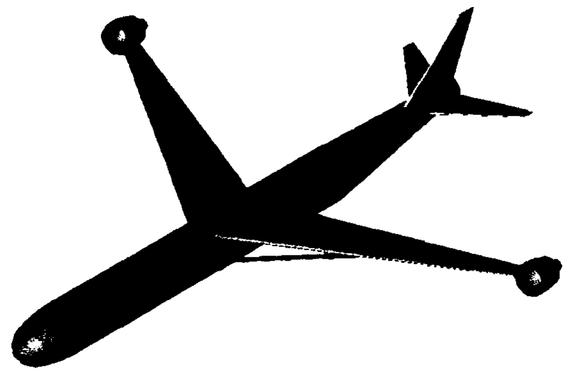
Fig. 9 Artist drawing of a powered lift channel wing with a CCW aircraft concept

Transonic Strut Braced Wings

Many general aviation pilots are quite comfortable with the concept of a strut-braced wing (SBW) because many of them learned to fly in aircraft of that type. The majority of the commercial transport aircraft today are low-wing, cantilevered concepts and although other concepts such as strut-braced and joined wings have been proposed, nothing has displaced them as of yet. Military transport systems are typically the opposite, and feature a high wing design philosophy. These differences in design philosophy result from very different operational requirements. In this section we will discuss the potential benefits obtained by re-examining the concept of strut bracing as applied to a transonic and supersonic vehicle.

The idea of a transonic strut-braced wing can be traced to the work of Pfenninger[64] in 1958. Follow on efforts for the Air Force by Kulfan and Vachal[65] and for NASA in the 1980's showed that the concept held promise. It was recognized at the time of these early studies that the design and analysis tools required to provide an efficient wing/strut juncture, which was so critical to the success of the concept, were not yet available. That started changing in the 1990's as Gundlach et al[66] presented results of a conceptual design study of a strut-braced wing (SBW) transonic transport. The assumed mission was for a 325 passenger, 7,500 nm range, and Mach 0.85 transport. They compared a 1995 technology cantilever wing design with an SBW concept. The SBW can potentially have higher aerodynamic efficiency, reduced weight, and a reduced wing thickness, which results in lower transonic wave drag. By reducing wing thickness a designer can unsweep the wing considerably, which may offer the potential for significant portions of natural laminar flow on the wing resulting in even lower drag. An added benefit of the reduced weight and improved aerodynamic efficiency is that smaller engines are required typically resulting in less noise. An MDO approach is necessary to take advantage of all the interdependencies. Two different SBW configurations were considered in this work and are shown in Fig. 10. One had the engines mounted on the wing tip, and the other had a T-tail with fuselage-mounted engines. The wing tip mounted engine configuration uses circulation control on the vertical tail to counteract engine-out yawing moments.

(a) Fuselage-Mounted Engines



(b) Tip-Mounted Engines

Fig. 10 Transonic strut braced wing (SBW) concepts (from reference 66)

A GE-90 class high-bypass-ratio turbofan engine is used for these vehicle studies. There are a variety of metrics that could be used for the optimization study, however, Gundlach used TOGW as the major figure of merit. As a final part of the study they studied the effect of incrementally adding advanced technology in the MDO process.

The study showed that in general the SBW concept has less wing area, higher aspect ratio, and a lower sweep than a conventional cantilever design. Gundlach states that: "Although the SBW has an 8.1% decrease in TOGW, the savings in fuel consumption are even more impressive. A SBW has a 13.6% lower fuel burn that a cantilever configuration when optimized for minimum TOGW ...". He reports that the SBW concept is very sensitive to aerodynamic technologies and is very synergistic. They recommend that greater emphasis should be placed on LFC, wave drag reduction, and other aerodynamic technologies for evaluation with the SBW. Coupling advanced flow and noise control technology could greatly increase the SBW benefits. Subsequent studies (unpublished) have shown when compared to an advanced (year 2010) conventional configuration, the strut-braced wing configuration had lower weight (over 10%), used less fuel (almost 20%), required smaller engines (required approximately 18% less thrust), and reduced emissions by 21%. All this without taking advantage of wing tip mounted engines, which were considered impractical in the 2010 timeframe. Here is a case where advances in propulsion technology (perhaps through distributed propulsion systems) will one day make the concept of wing tip propulsion systems practical.

Supersonic Strut Braced Wings

It would be fair to say that a great deal of effort has been directed toward the concept of supersonic commercial transports over the last 50 years in the U. S. including the Supersonic Transport Programs (SST) in the 1960's, the Supersonic Cruise Research (SCR) Program in the mid 1970's and early 1980's, and the NASA High Speed Research (HSR) Program in the mid 1990's. It would also be fair to state that in the United States, that these programs have been punctuated with long periods of relative inactivity in supersonic aerodynamics. As a result many of lessons from one program were relearned in the next program by completely different groups of aeronautical engineers. In fact, this lack of consistent research funding and support may well the one reason why the most recent U.S. production supersonic cruise capable aircraft in the current inventory is the B-1A developed in the mid 1970's. While much progress was made in those early programs from the standpoint of improvements in L/D, it is fair to state that relatively little has changed beyond the technology level of the Concorde, which has been in service for a quarter century. Cruise L/D levels have been improved in ensuing research programs from the nominal value of 7 (Concorde) to approximately 9 in studies conducted in the HSR program. As highlighted in the writings of Wood[67] and Bushnell[68], little true innovation has occurred beyond the pioneering efforts of R. T. Jones in the 1970's on 'oblique wing concepts' and Werner Pfenninger[69] in 1988 on 'highly swept arrow wings and strut braced wings. As discussed in the Bushnell reference, "Pfenninger, on the basis of synergistic flow control approaches, proffered an interesting and challenging design with and L/D value in the high teens." The concept similar to that shown in Fig. 11, features an extreme arrow wing planform, which is enabled by external strut bracing. Critical to the concept proposed by Pfenninger, is the requirement for significant runs of laminar flow on the wings. Pfenninger's concept relies on suction laminar flow control. Other interesting technology features of this configuration are discussed in references 68 and 69, but little has been done in NASA programs to seriously mature the current readiness level of the technologies required to achieve these double digit levels of cruise L/D which are required to make these vehicles economically viable. As noted by Wood[67], even fundamental work required to understand the unique features of arrow wings has not been done to address "the primary limiting factor of the planform, trailing edge separation." There are many technical challenges in the area of aircraft structures as well.

A great deal of focus on low boom efficient supersonic flight has been provided by DARPA's Quiet Supersonic Platform[70] (QSP) Program in the last two or three years. Some very innovative solutions were required to achieve the aggressive technology goals of the QSP program that included (among others) a sonic boom overpressure of 0.3 psf and a cruise L/D of 11. QSP results presented by Komadina[71] features down selected configurations containing highly swept arrow wings and the preferred concept featured a joined wing (or strut braced wing) as well as many other aerodynamic and structural technologies. A requirement for laminar flow was featured in most every QSP vehicle solution and as such would have to be considered as an enabling technology for any of the industry-proposed vehicle concepts. DARPA has provided significant funding for this fundamental research area. Work by Saric[43] and others was discussed previously in the Active Flow Control Technology section. Even if laminar flow control remains unachievable for the foreseeable future, some authors argue that there are still many drag reduction technology concepts which might result in large improvements in cruise L/D for supersonic aircraft. As noted by Wood[67] utilizing favorable interference effects from multiple bodies and wings, and utilizing wing upper and lower surface shaping to take advantage of the naturally occurring conical flowfield and pressure loadings are examples of drag reduction opportunities. He suggests that taking advantage of these opportunities " ... would correlate to a 30 to 40% increase in cruise L/D for a commercial supersonic transport". An aggressive, sustained research effort in a number of areas can overcome the technical barriers of economically viable supersonic flight.

Fig. 11 Sketch of a Pfenninger strut braced extreme arrow wing concept

Tilt Nacelle PAV

Pneumatic control and distributed engine technologies are being applied to a tilt nacelle concept based on the Grumman 698 design. The concept shown in Fig. 12, utilizes thrust vanes to generate all hover control authority. In addition, the concept uses pneumatic nacelles that provide pneumatic morphing of the nacelle allowing a virtual tailoring of the inlet and exhaust flow pattern. This will enable the designer to maximize the propulsion system performance throughout the flight envelope. Additional benefits include a reduction in the effective hover disc loading at the ground plane and a reduction in the ground erosion and foreign object damage (FOD) constraints.

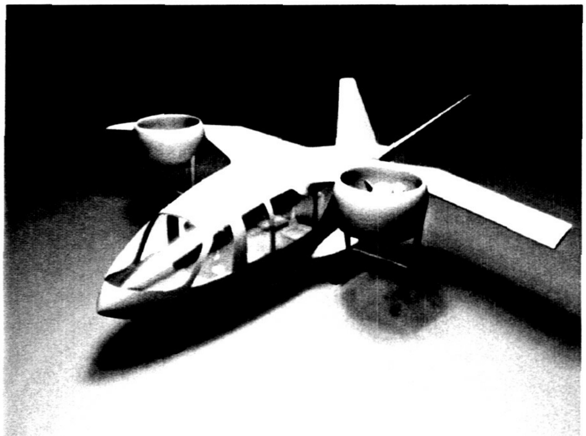


Fig. 12 Personal Air Vehicle Concept utilizing circulation control nacelles

Multi Gas Generator Fans (MGGF) may power the vehicle. The MGGF concept shown in Fig. 13, was developed by M-DOT Aerospace of Phoenix, Arizona and will utilize the exhaust of several small engines integrated in the nacelle to tip drive the nacelle's fan. Exhaust flow is then ducted onto a Coanda surface at the nacelle exit for pneumatic control of the exhaust diffuser. Coupling the pneumatic nacelle with the MGGF concept provides the smallest propulsion system power requirement possible for V/STOL. Because the MGGF contains a number of small-distributed engines, their use to power the nacelles should result in a relaxing of the engine-out sizing constraint for hover and approach. Typically this constraint determines the engine size; hence, dramatic reductions in the required thrust to weight of the vehicle for safe operations are possible. In this specific case, required thrust to weight reduces from approximately 2.4 for a conventional twin-engine concept, to about 1.4 for the MGGF concept while also eliminating the need for an engine cross-shafting system. For low speed operations such as hover and transition to forward flight, the pneumatic nacelle utilizes virtual inlet lip shaping to provide a more favorable, bellmouth lip shape that may effectively double the maximum thrust at these conditions. It also may provide nacelle separation control in transition and crosswind conditions. A recent study showed that only 4% of all propulsion system problems were related to the fan, while 71% were due to gas generators making the redundancy of the MGGF a potentially safer system. The combination of these two technologies makes for a more robust and safe aircraft system.

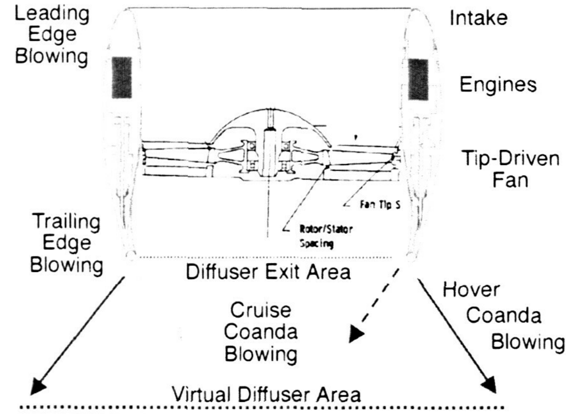


Fig. 13 Sketch of the Multi Gas Generator Fan concept with pneumatic leading- and trailing edge blowing

Crosscutting Technologies

Roles and Challenges for Computational Approaches

To seriously consider revolutionary changes in aerodynamic vehicles requires working outside of the comfortable design space of the past, preferably with tools that take more advantage of both developing computational capabilities and existing knowledge bases. In this section, we will discuss directions that we believe the computational community can and should be taking to better facilitate the design of novel aerodynamic vehicles.

Integrating the stovepipes

In the past, CFD, or computational fluid dynamics, dominated our computational efforts in aerodynamics. As a first step into the future, we need to generalize the concepts that need to be included in such computational efforts. The importance of design optimization across numerous specialties, including fluid dynamics, acoustics, aeroelasticity, stability and control, and structural mechanics highlights the ultimate goal of developing packages that permit coupling these specialties together at various levels. Although we will continue to require computational capabilities that are particularly efficient and/or accurate for solving specialized problems, the ability to couple results from multiple disciplines into a comprehensive design scheme will become more critical in the future. Rather than thinking just in terms of CFD, code developers need to start thinking about computational aeronautics, or at least computational aerodynamics.

In the broader context of computational aeronautics, the need for more efficient solvers, perhaps running on computer architectures that we can just barely imagine, will extend long into the future. Some individuals may assert that we cannot assimilate information fast enough to warrant increased code speed beyond a certain point. Here we assert that limited capacity to absorb all the data produced may be an observation of current practice, but not a limitation of planned capability. As current computations take less time, the impetus to exploit the results of those calculations in more and more inclusive system-design packages will grow. We have plenty of work to fill the computers of many generations to come.

As part of this process, accelerated development of physics-based models for complex flow phenomena is going to be critical. Although improvements in computing power and solver techniques will continue to facilitate more direct computations of particularly complex physical phenomena, relying on improved computations to justify neglecting the hard work of model development will seriously hamper our ability to reliably design vehicles with configurations outside our current comfort zone.

The need for modeling

Large-Eddy Simulation (LES) involves the computation or simulation of large turbulent eddies while the dissipation of the unresolved smaller scales of motion is modeled. Proper application of LES requires that the cutoff length scale between the computed (and therefore resolved) turbulent eddies and the unresolved turbulence be in the inertial range of turbulence. The appropriate use of LES has led to important improvements in turbulence modeling as well as to deeper insights into the physics of complex flows. Some individuals believe that continued improvements in computer hardware and software will enable LES to dominate future aerodynamic calculations and therefore further work on ways to model complex flow physics is simply not required. In our opinion, such a belief is overly optimistic and will negatively impact the development of the kind of computational tools necessary for ultimately designing revolutionary aircraft.

To better appreciate this situation, first consider the estimates of Spalart, et al[72] for the resources required for performing an LES over a wing of transport aircraft in cruise. After making a series of optimistic estimates of our future ability to accurately perform such a calculation, Spalart, et al[72] conclude that approximately 10^{11} grid points would be required, resulting in a computational effort of approximately 10^{20} floating point operations to complete. With a rough trend of a factor of 5 increase in computer power every 5 years, they estimate that roughly 8 periods of 5-fold increases would be required; hence such a computation might attain Grand-Challenge status in the late 2030's. How much longer it would take to incorporate such a computation into a design cycle is unclear.

Some individuals have criticized the Spalart, et al[72] estimates as being overly conservative in terms of the computer power trend, but to our best knowledge, no serious criticisms have been leveled against the work estimated to be required to perform the computation. Hence recomputing the year in which such a calculation would reach Grand Challenge status based on more optimistic computer improvements is easily done by equating the estimated 5^8 increase in computer power to that predicted using some other improvement scaling. Assuming a doubling of computer power every year, an incredibly optimistic long-term projection would leave us with such a calculation rising to Grand Challenge status in about the year 2015. Again, considerable additional improvements would be required for such a calculation to become part of the design cycle -- and this is just a cruise-configured wing, no fuselage, no high-lift system, no landing gear, etc. The point is that foreseeable improvements in computer hardware and software alone will not enable us to simply compute our way through difficult physics. For a very long time into the future, we will retain a need to develop models of complicated physics and use those models as part of computations involving aerodynamic vehicles. Successful physical modeling is going to be especially required for optimization studies, where multiple runs with several types of interacting phenomenon are required.

Physics-based modeling

Although greatly enhanced computing power allows us to solve equations much more rapidly and accurately than in the past, we must be solving the proper equations that suit the problem. Vos et al.[73] indicate that appropriate modeling of the physics is critical.

Transition and turbulence treatments

The general modeling of turbulence and the laminar-turbulent transition problem has proven to be one of the most daunting problems in engineering physics. The wide range of scales of turbulent flows, the extraordinary sensitivity of transition to initial and boundary conditions, and the great difficulty in measuring flow details in critical regions all contribute to the problems.

Although turbulence is inherently unsteady, considerable progress has been made in the development of turbulence models for cases in which the flow is quasi-steady, i.e., flow structures on the order of the macroscopic scales of interest are substantially steady. However, recent years have seen a tendency to acknowledge that flows with large-scale separations, or where the important scales of motion are of the same order as the turbulent motions, should be treated as unsteady. After recognizing that LES will not solve all our turbulence issues, a wide variety of turbulence treatments have emerged to bridge the gap between unsteady LES with its huge computing requirements and steady Reynolds-averaged Navier Stokes (RANS) computations, which are now routinely performed. These methods go by a variety of names, including Detached Eddy Simulation (DES)[72,74,75,76] Limited Numerical Scales (LNS)[77], Flow Simulation Methodology (FSM)[78], Partially Averaged Navier Stokes (PANS),[79] and others[80]. They all involve performing an unsteady LES-like simulation in regions where the unsteady flow structures are well resolved by the grid and a more dissipative RANS-like calculation in regions where the unsteady flow structures cannot be resolved. Which approach is the best, or even what critical experiments should be used to test the models and make choices between them is not at all clear. An important step in the direction of sorting out benefits and deficiencies of each treatment would be to perform a set of critical experiments with carefully measured flow quantities to form the basis for comparisons between the models. This work is actually being performed as part of the NASA Langley Research Center Workshop on CFD Validation of Synthetic Jets and Turbulent Separation Control to take place at NASA Langley Research Center in March 2004. This workshop is being conducted in collaboration with U.S. and European research organizations.

Modeling the laminar-turbulent transition process brings additional difficulties not addressed in the search for suitable turbulence models and treatments. Many of these difficulties stem from a lack of knowledge of the details of the upstream conditions. Rubinstein and Choudhari[81] applied stochastic versions of transition models to this problem. In particular, they explored a resonant triad model with random forcing of the phase equation, a multi-mode critical layer theory, and a stochastic form of the parabolized stability equations. Considerable additional work needs to be done to integrate any of these approaches with modern turbulence modeling.

The long-term future of turbulence and transition modeling will require a combination of hard work to improve current approaches dispersed with occasional new ideas to force the turbulence and transition community to re-assess its direction and consider whether some dramatically different approaches might well yield improved efficiency and/or accuracy in the long term. For instance the application of wavelets to turbulence modeling has yet to make serious inroads. Ideas from Lattice-Boltzman solvers (for example, see Chen et al.[82]) may also provide new insights for turbulence simulations, even in cases in which the more traditional Navier Stokes equations are solved.

<u>Boundary conditions</u>

Interest in active flow control for drag or noise reduction, flow vectoring, mixing enhancement, and separation control has stimulated the recent development of innovative synthetic jet actuators that create localized disturbances in the flowfield. A difficult problem associated with these actuators involves the coupling between the flow structures interior to the actuators and the effect of the actuators on the external flow. Difficulties have arisen even in the simulation of single, or a small number of these devices, so considerable concern exists with respect to modeling the effects of large numbers of actuators in boundary layers at high Reynolds numbers. Carpenter et al [83] review a variety of approaches to the problem. Much more work is needed to validate the various approaches under different sorts of flow conditions.

<u>Noise sources</u>

The computation of aircraft noise is a particularly difficult task because of large disparities between the relevant scales. Acoustic waves involve very small amounts of energy relative to localized hydrodynamic fluctuations and the acoustic waves are very sensitive to numerical errors. In addition, the important frequency range is large, extending from several hundred Hz to about 10 kHz. Finally, the scales involved in acoustic propagation are typically much larger than those involved in its generation. Extensive work in Computational AeroAcoustics (CAA) is underway at a variety of institutions to address many of these issues.[84,85,86] Simply propagating the acoustics is a significant job. Singer and Guo[87] determined that resolving all the frequencies important for noise certification with 6-7 points per wavelength over a volume encompassing a medium size commercial transport requires as many as 10^{11} grid points, approximately the same as that estimated by Spalart et al[72] for an LES over a wing.

Schemes for modeling the noise sources through the development of synthetic turbulence[88,89] are currently under development as well as approaches for coupling hybrid RANS-LES computations with acoustic propagation schemes[90]. How to do this well for general flow conditions still requires significant research. What is the most effective approach for modeling a noise source and propagating it is far from clear.

Future revolutionary aircraft will require both low airframe and exhaust system noise. The ability to predict installed jet noise from complex three-dimensional flows is an absolute requirement. One promising approach, which is being developed at NASA Langley, is documented in the work of Hunter and Thomas[91]. The method is based on Lighthill's

Acoustic Analogy and uses a Navier Stokes RANS CFD simulation with temperature-corrected two-equation k-e turbulence closure and anisotropic Reynolds stress modeling. It is hoped that this work represents an initial step in a general 'design for noise' capability.

Algorithmic developments

Probabilistic Methods

Traditional analysis employs deterministic methods. The conditions to be evaluated are preselected and used as inputs, a set of model equations are solved, and outputs corresponding to the inputs are obtained. The extent to which the outputs characterize physical reality depends on a number of factors, including: how well have the model equations been solved, how well do the model equations describe the relevant physics, and how well are the input parameters known. A new research program at NASA Langley Research Center is being developed to explore these issues in more depth.

One tool that might be used involves probabilistic problem solving. In probabilistic methods, uncertainties (usually in the form of probability distribution functions) are included as part of the input. The output is not a single value for any quantity, but another probability distribution function that characterizes the output value. Probabilistic problem solving is making inroads, especially into the design of structural components.[92] We anticipate that such methods will start to appear in aerodynamics, where the strong nonlinearity in the system has the potential for making the computed outputs very sensitive to the inputs. The incorporation of such methods into aerodynamic design will ultimately allow for rigorous risk-based design.

In the realm of aerodynamics, probabilistic methods can also be used to assess the very tools that we employ to make the predictions. For instance, we currently have a great deal of uncertainty in the prediction of aerodynamic parameters just from the application of different computer codes.[93] Future developments may help us account for those predictive uncertainties, clue us as to how those uncertainties vary with different types of aerodynamic problems, and guide us in ways to reduce the uncertainties.

Optimization methods

How to tweak a design to achieve a desired result is going to be critical to taking full advantage of revolutionary configurations. One of the difficulties with any revolutionary change is that the early versions of the new idea rarely perform as well as the best designs of the prior approach. Years of experience with a single approach helped drive the details of that design towards a local optimum. Although some new approach will not have the benefit of those years of experience, appropriate use of optimization methods can narrow and perhaps eliminate that initial performance penalty. Rather than slowly evolving to the optimal choice of details for any new configuration, based on years of experience with similar designs, optimization methods have the potential for greatly accelerating the move towards those best design details. With such methods in place, new configuration ideas can be compared with their older counterparts on a more equal footing.

Beyond the fact that the work requires CFD experts, a number of important technical issues still stand in the way of the widespread use of design optimization methods. One of the difficulties with using state-of-the-art optimization methods has been the high computational cost of repeated function and derivative evaluation via high-fidelity analyses and sensitivity analyses. This difficulty is being addressed from two directions: design oriented model development and improved optimization strategies. The first area seeks to reduce the cost of computing functions and derivatives in the context of design. While some promising optimization approaches do not rely on derivatives, they severely limit the dimensionality of the optimization problem. Thus, for aerodynamic design problems of even medium size, computing derivatives is now a necessity. The recent trend of using adjoint methods for computing sensitivity derivatives is aimed at making such calculations affordable. For the price of solving a single additional linear problem and a subsequent matrix-vector multiplication dimensioned by the number of design variables, design sensitivities can be computed for a single output or constraint function. Unfortunately, the solution of the adjoint system for realistic aerodynamic problems has been difficult. Recent work by Nielsen, et al[94] shows that an exact dual algorithm guarantees asymptotic convergence rates equivalent to that of the primal system, including applications to turbulent flows. By simultaneously solving adjoint systems for several output functions, a significant savings in the context of multiobjective and constrained design can also be realized. The second area seeks to reduce the cost of design via a rigorous use of variable-fidelity models with a single optimization process. One optimization strategy developed by Alexandrov and Lewis[95] at the NASA Langley Research Center relies on transferring the computational load onto low-fidelity models, occasionally but systematically corrected with high-fidelity information. The approach, first order Approximation/Model Management Optimization (AMMO), can significantly reduce the number of high-fidelity model evaluations, while retaining convergence to high-fidelity optima. The method has the potential for being particularly effective in the presence of a hierarchy of models of increased fidelity. Current demonstrations of the approach indicate that not only can lower resolution simulations be used to accelerate convergence of a higher resolution simulation to an optimal design, but the Euler equations can be used to accelerate convergence to an optimal design for an inherently viscous flow problem. Practical efficiency of the method is problem-dependent, but the promising results to date suggest that the approach merits further investigation. For instance, AMMO might take advantage of various levels of turbulence modeling or it might be useful in combination with models for local applications of active-flow control devices. Other difficulties in using formal optimization methods include appropriate optimization problem formulation, robust mesh movement for viscous grids, adaptive gridding, and automatic specification of design variable bounds.

Automatic error control

As discussed previously, significant solution variability exists between different aerodynamic solvers run on the same nominal problem. The wide variability was documented in the first AIAA Drag Prediction Workshop[96]. The use of various physical models, such as those for turbulence, chemistry, and boundary conditions, contributes heavily to these differences. However, independent of the physical models used, different solvers exhibit different results if approximation fidelity is insufficient. Inadequate grid resolution in space or time is the primary source of this variance. Different formulations (Finite-Element / Finite-Difference / Finite-Volume), or different approximation order can yield vastly different answers if the grid resolution is inadequate. This issue is not easily remedied in three-dimensional computations, where resources are often pushed to their limits. Automatic error control would provide the capability to specify the desired error tolerance of an output variable and have the code vary internally to achieve the specified tolerance. This ability would allow designers to concentrate more on the outcome of a calculation, and not the details involved in ensuring accuracy of the output. This is especially important in cases where each output is not scrutinized by a human, but instead becomes the input to another computer routine. Automatically producing an output to a specific tolerance is crucial to multidisciplinary design methodologies.

Errors associated with inadequate spatial resolution have long plagued computational fluid dynamics. Poor spatial resolution can change not only quantitative results, but also the qualitative features of the flow. Early attempts to enable automatic grid adaptation focused on increasing grid resolution in regions of rapid geometry or flow-solution change to target local equation or discretization errors. These feature-based grid refinements did not necessarily improve the accuracy of the quantity of interest (typically, lift and/or drag), although they did reduce the number of grid points. More recent work has linked local equation error to global solution quantities through the solution of both the primary flow equations and the dual, or adjoint equations.

Venditti and Darmofal[97] have demonstrated 2D adjoint error correction methods to compute output functions for high Reynolds number turbulent flow on complex, multi element geometries. An estimate of the remaining error in the output function after application of the error correction step is also used as an adaptation criterion. The adjoint adaptation criteria (a combination of interpolation error estimates and equation residuals for the primal and dual problems) is extremely effective in directing grid resolution to directly impact the solution quantity of interest. Targeting the remaining error focuses the adaptive procedure on the nonlinear errors in the flow field to improve the error corrected functional.

Park[98] is currently extending these methods to 3D flows with direct CAD coupling to adaptation and has demonstrated ten-fold reductions in grid requirements for solutions with equivalent errors. A particularly important implication of this methodology is the fact that the error remaining in the simulation at termination was always within a user-specified tolerance. Extension of this work to cases in which multiple quantities must be accurately computed simultaneously, as well as to time-dependent flows remains to be done. An added benefit to this approach is that the adjoint solution is also available for design optimization.

Schemes for automatic error control in temporal integrations are available, but not widely used[83]. The perceptual bias towards ignoring temporal accuracy needs to change as the community begins to tackle more complicated unsteady flow problems. Temporal error consists of truncation error (discrete approximation of a continuous temporal derivative), and algebraic error (finite residual remaining after each timestep in the nonlinear system of algebraic equations). Both must be reliably predicted and balanced to optimize the efficiency of a given scheme. High-order temporal schemes offer potential increases in efficiency over presently used methods, but must be carefully tuned to utilize different solver technologies. Robust algebraic solvers are necessary to realize the benefits of high-order methods.

Understanding results

As we become more proficient at generating gigabytes, and eventually terabytes of computational data, we need to pay more attention to the development of more sophisticated systems to analyze and visualize the data. Although extracting a single number, like lift or drag, might be straightforward, visualizing and conceptualizing even a moderately extensive set of field data is nontrivial. Using full flow-field computational (or extensive experimental) data to isolate and model important features of the flow can challenge the sanity of any investigator. Therefore, in conjunction with the development of more capable numerical techniques, we need a sustained effort to develop postprocessing tools that can help us optimize the use of the computed data.

Feature-recognition software will probably be indispensable in efforts to understand flow phenomena. Not only do we need research in generic feature recognition to continue, but also we need to better understand what flow features should be isolated and how those flow features might interact with each other.

Visualization has traditionally dominated our analysis tools; however, the time-dependent, three-dimensional nature of turbulent flows makes most any visualization difficult. Ideally, a researcher would like to immerse him/herself in the flowfield and analyze it from all points of view. To date, such immersive analysis is in its infancy. Cave Automatic Virtual Environments[99] (CAVE), in which images are projected on multiple walls of a room and the images vary in response to head movements of the observer, have been developed for analyzing transitional and turbulent flows (for example, see Banks and Kelly[100]). However, the environment is expensive to produce, not easily accessible to individual researchers, and the ability to control the details of the visualization is not yet sufficiently intuitive for such visualizations to become generally useful to the research community. Projections of holographic images in small workstation environments may be more successful, or at least reach more researchers. Voice activation of image control might facilitate the interaction of the researcher with the dataset. Such developments may lead to important insights in the future.

Although the flashy, high-tech sort of visualization described above tends to capture attention at shows and exhibits, one of the more difficult outstanding visualization problems for researchers in fluid mechanics involves more fundamental and less glamorous needs. Even in nominally steady flows, three-dimensional tensor fields are notoriously difficult to visualize. The introduction of underused visual cues such as texture may eventually provide improved insight into these fields. Developing these tools will require individuals to work at the edges of traditional disciplines and will benefit from nontraditional collaborations of researchers.

Non-traditional solver techniques

In recent years, methods using the lattice-gas automata (LGA) and the lattice Boltzmann equation (LBE) have become an alternative to conventional computational fluid dynamics methods for various systems (for example, see references [101,102,103]). The fundamental philosophy of the LGA and LBE methods is to construct simple models based on kinetic theory that preserve conservation laws and necessary symmetries such that the emerging behavior of these models obeys the desired macroscopic equations. The great promise of LBE methods follows from their intrinsic parallelism due to nearest neighbor data communications of the convection process and a purely local calculation of the collision process.

Although the promising potential of the LGA and LBE methods as viable CFD tools has been demonstrated in a number of cases of laminar and (in the case of direct numerical simulation) turbulent flows, these methods have not been developed to address the specific needs of computational aerodynamics. (See Lockard et al[104] and a more recent opposing view by Shock et al[105] In particular, these methods are usually restricted to structured Cartesian grids of square/cubic cells, so the calculation becomes impractically large where boundary layers need to be resolved. Although in principle, interpolations can be applied to develop stretched grids in these methods, the effects of the interpolations still need to be studied in depth. A second unresolved issue for these methods involves the development of fast algorithms for steady state calculations. At present, LGA and LBE methods are essentially explicit time marching schemes. Algorithms with multi-grid type of solution techniques are yet to be fully developed, although preliminary studies in this direction have been done. A third issue important for aerodynamic calculations is related to turbulence modeling, without which these methods would not be useful to high-Reynolds-number aerodynamic calculations. Another issue is the current limitation of the methods to low-speed flows, at least if we wish to take advantage of the efficiencies associated with having a small number of velocities. Finally, a systematic method to develop high-order LBE schemes is highly desirable. Currently the accuracies of the LGA and LBE methods are essentially first order in time and second order in space. If these issues can be resolved, LGA and LBE methods may play a more significant role in future computational aerodynamics and acoustics.

Solvers that learn

Although computer programs that learn from the consequences of their past actions have been popular in games (most notably chess) and robotics, learning behavior in aerodynamics programs seems to be limited to adaptive gridding and design optimization. In these cases the learning is restricted to a single run or set of runs – the learning does not change the program itself and let it benefit from its past experiences. However, programs that can modify themselves, or at least be smart enough to offer to modify themselves or their input in view of apparent code or user difficulties have the potential for dramatically improving the quality and quantity of computations that are performed. As food for thought, we consider two cases below.

In the first case a database is populated with information associated with information associated with previous runs. The information might include grid resolutions, turbulence model information, etc. Some sort of evaluation of the performance would also need to be included. Right now it is hard to imagine this evaluation being done by the computer itself, but this may be possible in the future. Future cases run with the code would have access to the database and an intelligent program would be capable of determining similarities between the new flow case and one or more previously run cases. The intelligent program would then be able to make recommendations as to what turbulence model or what grid resolution should be used to efficiently compute the new case.

As a second example, steady Reynolds-averaged Navier Stokes calculations sometimes experience exponential instabilities when the local CFL number grows too large. Oftentimes, this is the result of a transient that would correct itself through further iterations if the calculation could just be kept stable through the transient. Therefore one of the first strategies for dealing with such a problem, is to re-perform the calculation, stopping sometime before the instability appears, reducing the iteration time step (and thereby lower the CFL number), and then continuing the calculation, hopefully bypassing the transient, and in the most optimistic circumstances, returning to the original time step. Humans are apparently trainable; they can learn to recognize CFL instabilities and follow something like the above procedure. A smart wrapper around the solver code might observe its user perform this procedure several times and then be able to perform the procedure itself. At first, the program should probably request permission to perform the required sequence of steps. Later, as both user and program become more confident, the program might just alert the user as to what it is doing. Extensive sets of carefully reviewed learned procedures might even find a lucrative market for themselves.

Wrap-up

Advanced computer tools will have an important role to play in the development of revolutionary new aerodynamic vehicles. Just as the new vehicles will require integrating a variety of disciplines to maximize the benefit, computational methods for a variety of fields will need to be built in ways that allow more interaction with other codes designed for solving problems in other fields. Integrating codes in ways that can lead to improved designs will be a challenging task in and of itself.

Among other things, the need for integration will continue to drive the need for better modeling of flow physics and improved algorithms for getting accurate results in the shortest time possible. Novel algorithms for solving systems on reconfigurable hardware platforms may be required to achieve the speeds required.

Codes that include adaptive behavior and hopefully learn from past experiences have potential for greatly facilitating our ability to design novel aircraft.

We want to ensure that past paradigms do not bind our future directions. We need to concentrate on approaches that achieve our desired outcomes and not necessarily those that seek to maximize output. Smart algorithms, perhaps running on advanced hardware platforms are a route to reaching our goals.

Concluding Remarks

The paper discusses the current perception that aeronautics and aerodynamics in particular, is a mature technology. It highlights work that was done in the development of a NASA Blueprint for Aeronautics that describes a revolution in aeronautics, and efforts at NASA Langley to develop roadmaps for various disciplines. Background information in the paper describes the environmental factors that will affect aviation's future, and the accelerating progress in computer processing speed and its impact on computational predictions and artificial intelligence.

The future is not easy to predict, and if the trends of increased restrictions on noise and emissions are realized, the current generation of aircraft will have difficulty meeting these goals. Revolutionary new vehicles will be required to meet the NASA goals for reduced emissions and noise. These new vehicles will require us to change our paradigm in vehicle design. Examples are provided that show that revisiting previous innovative vehicle concepts and incorporating new technologies to remove prior barriers and add new capability can help. Developing radically new concepts will require improvements in our conceptual design capability and an expansion of our fundamental knowledge base. The ability to accomplish conceptual design studies rapidly, with a known level of confidence and tailored fidelity was considered to be a priority. It will require nurturing specific crosscutting technologies including computational methods and multi-disciplinary analysis and optimization. A strong effort to reduce drag in all it forms, and eliminate or reduce noise at its source is a requirement.

The future in aerodynamics is inherently multidisciplinary where new flow and noise control technologies add new capabilities and are brought into the design process at the earliest stages. Instead of avoiding structural flexibility, we will exploit it, either through small local or large global shape changes. The future vision therefore will require a fundamental paradigm shift from the steady to unsteady world, from passive to active, and from rigid to flexible, all with the goal of continuously optimizing a vehicles performance throughout its flight envelope. The greatest technical challenges and opportunities occur at the intersections of disciplines, but the real barriers may be cultural and not technical. Providing a workforce with the skills and aptitude to work at the intersections will be a challenge.

In the new paradigm for the future, aerodynamics is not mature. We are in fact at a new beginning both in terms of our fundamental knowledge base and our ability to predict. Revolutionary new vehicles with exciting new capabilities offer the prospects of new levels of mobility for the public with reduced impact on our environment.

Acknowledgements

The authors would like to gratefully acknowledge the other participants of the Aerodynamics Roadmap Team that included from NASA Langley, Charlotte Whitfield, Bob McKinley, Jim Pittman, and Long Yip, and Prof. William Mason of Virginia Tech University. Many other individuals have contributed substantially to various sections of this document. The authors would like to acknowledge the assistance of: Natalia Alexandrov, David Banks, Mark Carpenter, Li-Shi Luo, Joseph Morrison, Eric Nielsen, Michael Park, Robert Rubinstein, Christopher Rumsey, and Mike Walsh.

References

1 Schneider, Wolfgang: "The Importance of Aerodynamics in the Development of Commercially Successful Transport Aircraft", CEAS/DragNet European Drag Prediction Conference 2000, Potsdam, Germany, 19-21 June 2000.

2 Dexter, P. C.: "A Strategic European Approach to Aerodynamics Research, Technology, and Development", Aero Journal, August 2001, pp. 451-457.

3 Group of Personalities, "European Aeronautics: A Vision for 2020 – Meeting Society's Needs and Winning Global Leadership", 2001. Available online at: http://europa.eu.int/comm/research/growth/aeronautics2020/en/

4 *"The NASA Aeronautics Blueprint – Toward a Bold New Era of Aviation"*, 3 Jun. 2002, http://www.aero-space.nasa.gov/aero_blueprint/index.html

5 Abey-Wickrama,L., a'Brook,M.F., Gattoni,F.E.G., and Herridge,C.F., "Mental hospital admissions and aircraft noise," *Lancet* 2 pp.1275-1277, 1969.

6 Meecham, W.C., and Shaw,N.A., "Increase in mortality rate due to aircraft noise," *Proc. of Inter-Noise 93* Leuven, Belgium, 1993.

7 Powell, C. A. and Preisser, J. S.: "NASA Subsonic Jet Transport Noise Reduction Research", Aero Journal, August 2000, pp. 353-358

8 Schmitt, Dieter: "Challenges for Unconventional Transport Aircraft Configurations", Air and Space Europe, Vol. 3, No. 3/4, 2001pp 67-72

9 Panel on Atmospheric Effects of Aviation: "The Atmospheric Effects of Stratospheric Aircraft Project – An Interim Review of Science an Progress", National Research Council, National Academy Press, Washington, D.C., 1998

10 Intergovernmental Panel on Climate Change: "Aviation and the Global Atmosphere", Cambridge University Press, 1999.

11 Green, J. E.: "Greener by Design – The Technology Challenge", The report by the Technology Sub Group, Aero Journal, February, 2002, pp. 57-106

12 "The Environmental Effects of Civil Aircraft in Flight", Royal Commission on Environmental Pollution, 2002

13 Arthur D. Little Ltd: "Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK", DETR/71861/10rep.doc, 2000

14 Minnis, P., Young D. F., Nguyen L., Garber D. P., Smith Jr., W. L., and Palikonda, R.: "Trans-formation of Contrails into Cirrus During SUCCESS", Geophys. Res. Ltrs., 25, 1157-1160.

15 Minnis, Patrick; Nguyen, Louis; Duda, D. P.; and Palidonda, R.: "Spreading of Isolated Contrails During the 2001 Air Traffic Shutdown", 10th Conference on Aviation, Range, and Aerospace Meteorology, Portland, OR, 13-16 May, 2002

[16] NASA Press Release No. 02-035, "NASA Scientists Use Empty Skies to Study Climate Change", 13 May, 2002.

[17] Szodruch, Joachim, and Hilbig, Reinhard: "Building the Future Aircraft Design for the Next Century", 36th AIAA, Aerospace Sciences Meeting & Exhibit, AIAA Paper 98-0135, Reno, NV, Jan. 12-15, 1998

[18] Gelsinger, Pat: "Moore's Law Extends and Expands for the Future", available at, http://www.intel.com/labs/eml/painterview.htm

[19] "New Transistors for 2005 and Beyond", available online at: http://www.intel.com/research/silicon/micron.htm

[20] Gasser, Bob: "Nanotechnology in Electron Devices", American Institute of Chemical Engineers Meeting (AIChE), February, 11, 2003

[21] Moravec, Hans: "Robot – Mere Machine to Transcendent Mind", Oxford University Press, 1999

[22] Kurzweil, Ray: "The Law of Accelerating Returns", available online at: http://www.kurzweilai.net/articles/art0134.html

[23] Dongerra, Jack: "High Performance Computing, Computational Grid, and Numerical Libraries", 14th Symposium on Computer Architecture and High Performance Computing, Vitoria/ES-Brazil, October 28-30, 2002

[24] http://www.top500.org

[25] Liebeck, R.: "Design of the Blended-Wing-Body Subsonic Transport", AIAA-2002-0002, 40th AIAA Aerospace Sciences Meeting, Reno, NV 14-17 January, 2002

[26] McMasters, John H. and Cummings, Russell M.: "Airplane Design – Past, Present, and Future", Journal of Aircraft, Vol. 39, No. 1, Jan-Feb, 2002

[27] Dreisbach, Rodney L.: "Trends in the Design Analysis of Aerospace Vehicles", Daratech iDPS 2001 Conference on Intelligent Digital Prototyping Strategies, Novi, MI, 29-30 October, 2001

[28] National Research Council, Aeronautics and Space Engineering Board: "Commercial Supersonic Technology: The Way Ahead", National Academy Press, Washington, D.C., 2001

[29] Gad-el-Hak, M., "Introduction to Flow Control", in *Flow Control: Fundamentals and Practices*, Springer-Verlag, 1998, pp. 1-108.

[30] Kumar, Ajay, and Hefner, Jerry N.: "Future Challenges and Opportunities in Aerodynamics", Proceedings of the 22nd International Congress of Aeronautical Sciences, Harrogate, U.K., Aug.27-Sept.1, 2000. Also published in The Aeronautical Journal, vol. 104, No. 1038, pp. 365-373, Aug. 2000.

[31] Thomas, Russell H., and Choudhari, Meelan M.: "Flow and Noise Control: Review and Assessment of Future Directions", NASA TM-2002-211631, April, 2002

[32] Lord, W. K., MacMartin, D. G., and Tillman, T. G.: "Flow Control Opportunities in Gas Turbine Engines", AIAA 2000-2234, Fluids 2000, Denver, CO, 19-22 June, 2000

[33] Lin, J. C.: "Control of Turbulent Boundary-Layer Separation using Micro-Vortex Generators", AIAA Paper 99-3404, 30th AIAA Fluid Dynamics Conference, Norfolk, VA, June 28-July 1, 1999.

[34] Lin, J. C.: Review of Research on Low-Profile Vortex Generators to Control Boundary-Layer Separation. *Progress in Aerospace Sciences*, v. 38, issue 4-5, 2002, pp. 389-420.

[35] Walsh, M.J. "Riblets," , *Viscous Drag Reduction in Boundary Layers*, Vol. 123, Ed. D.M. Bushnell and J.N. Hefner. Washington, DC:, American Institute of Aeronautics and Astronautics, Inc., 1990, pp 203-261.

[36] Walsh, M. J., Sellers, W. L. III, and McGinley, C. B. Riblet Drag at Flight Conditions. Journal of Aircraft , Vol. 26, No. 6, June 1989, Pages 750-575.

[37] McLean, J. D. , George-Falvy, D. N., and Sullivan, P. P. "Flight –Test of Turbulent Skin Friction Reduction by Riblets," *Turbulent Drag Reduction by Passive Means*; Proceedings of the International Conference, London, England, Sept. 15-17, 1987. Volume 2 . London, Royal Aeronautical Society, 1987, p. 408-424.

[38] Szodruch, J. : "Viscous Drag Reduction on Transport Aircarft", AIAA Paper 91-0685, 29th Aerospace Sciences Meeting, Reno, Nevada, January 7-10, 1991.

[39] Drewer, D.: "Riblets Enter Service", Flight International, Vol. 27, August, 1988

[40] Marec, J.-P.: "Drag Reduction: A Major Task for Research", CEAS/DragNet European Drag Reduction Conference, Potsdam, Germany, 19-21 June 2000.
[41] "Drag Reducing Riblets" Aerospace Engineering, December, 1989, pp. 39-42.
[42] Viswanath, P. R., "Aircraft Viscous Drag Reduction Using Riblets." *Progress in Aerospace Sciences,* Volume 38, pp. 571-600, 2002
[43] Saric, W. S., Carrillo, R. B., and Reibert, M. S.: "Leading-Edge Roughness as a Transition Control Mechanism", AIAA 98-0781, AIAA, Aerospace Sciences Meeting & Exhibit, 36th, Reno, NV, Jan. 12-15, 1998
[44] Washburn, A. E., Gorton, S. Althoff, and Anders, S. G.: "Snapshot of Active Flow Control Research at NASA Langley", AIAA 2002-3155, AIAA 1st Flow Control Conference, St. Louis, MO, 24-26 June, 2002
[45] Joslin, R. D.: "Overview of Laminar Flow Control", NASA TP-1998-208705, 1998
[46] Joslin, R. D.: "Aircraft Laminar Flow Control", *Annual Review of Fluid Mechanics,* Vol. 30, pp.1-29, 1998
[47] Arcara, P. C., Jr, Bartlett, D. W., and McCullers, L. A.: "Analysis for the Application of Hybrid Laminar Flow Control to a Long-Range Subsonic Aircraft", SAE Paper 912113, 1991
[48] Greenblatt, D. and Wygnanski, I., Control of Separation by Periodic Excitation, *Progress in Aerospace Sciences,* Volume 36, Issue 7, pp. 487-545, 2000.
[49] McLean, J. D., Crouch, J. D., Stoner, R. C., Sakurai, S., Seidel, G. E., Feifel, W. M., and Rush, H. M.: "Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft", NASA CR-209338, 1999.
[50] Englar, R. J.: "Circulation Control Pneumatic Aerodynamics: Blown Force and Moment Augmentation and Modifications; Past, Present, and Future", AIAA Paper 2000-2541, Fluids 2000 Conference and Exhibit, Denver, CO, June 19-22, 2000
[51] Jones, G. S., Viken, S. A., Washburn, A. E., Jenkins, L. N., Cagle, C. M.: "An Active Flow Circulation Controlled Flap Concept for General Aviation Aircraft Applications", AIAA Paper 2002-3157, 1st AIAA Flow Control Conference, St. Louis, MO, 24-27 June, 2002
[52] Munro, Scott E., Ahuja, K. K., and Englar, Robert J.: "Noise Reduction Through Circulation Control", AIAA Paper 2001-0666, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-11 January, 2001
[53] Stanewsky, E.: "Adaptive Wing and Flow Control Technology", *Progress in Aerospace Sciences,* Volume 37, Issue 7, pp. 583-667, 2001
[54] Breitbach, Elmar J., Anhalt, Christian, and Monner, Hans P.: "Overview of Adaptronics in Aeronautical Applications", *Air and Space Europe,* Vol. 3, No 3/4, 2001
[55] Kroo, Ilan: "Drag Due to Lift: Concepts for Prediction and Reduction", *Annual Review of Fluid Mechanics*, Vol. 33, 2001, pp. 587-617
[56] McMasters J. and Kroo, I. : "Advanced Configurations for Very Large Transport Airplanes", *Aircraft Design,* 1:217-42
[57] "Drag Reduction by Shock Boundary Layer Control – Results of the Project EUROSHOCK II Supported by the European Union 1996-1999", *Notes on Numerical Fluid Mechanics and Multidisciplinary Design,* Volume 80, eds. Stanewsky, Egon, Delery, Jean, Fulker, John, and Paolo de Matteis, Springer-Verlag, 2002
[58] Pendleton, Ed, Bessette, Denis, Field, Pete, Miller, Gerry, and Griffin, Kenneth: "The Active Aeroelastic Wing Flight Research Program", AIAA 1998-1972, 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference and Exhibit, Long Beach, CA Apr. 20-23, 1998
[59] Wood, Richard M, and Bauer, Steven X. S.: "Flying Wings/Flying Fuselages", AIAA 2001-0311, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-11 January, 2001
[60] Pasamanick, Jerome, "Langley Full-Scale-Tunnel Tests of the Custer Channel Wing Airplane," NACA RM L53A09, National Advisory Committee for Aeronautics, April, 1953
[61] Englar, Robert J., and Campbell, Bryan A.: "Pneumatic Channel Wing Power-Lift Advanced Super-STOL Aircraft", AIAA Paper 2002-3275, 1st AIAA Flow Control Conference, St. Louis, MO, 24-27 June, 2002

[62] Englar, Robert J., and Campbell, Bryan A.: "Pneumatic Channel Wing Power-Lift Advanced Super-STOL Aircraft", AIAA Paper 2002-3275, 1st AIAA Flow Control Conference, St. Louis, MO, 24-27 June, 2002

[63] Sellers, William L. III, Jones, Gregory S., and Moore, Mark D.: "Flow Control Research at NASA Langley in Support of High-Lift Augmentation", AIAA 2002-6006, Biennial International Powered Lift Conference, Williamsburg, VA, 5-7 November, 2002

[64] Pfenninger, W.: "Design Considerations of Large Subsonic Long Range Transport Airplanes with Low Drag Boundary Layer Suction", Report No. NAL-58-529 (BLC-111), 1958, Available from DTCI as AD-821759.

[65] Kulfan, Robert M. and Vachal, John D.: "Wing Planform Geometry Effects on Large Subsonic Military Airplanes", AFFDL-TR-78-16, U. S. Air Force, Available from DTIC as AD-A056-124.

[66] Gundlach, et.al.: "Conceptual Design Studies of a Strut-Braced Wing Transonic Transport", *Journal of Aircraft*, Vol. 37, No. 6, Nov-Dec, 2000

[67] Wood, Richard M., Bauer, Steven X. S., and Flamm, Jeffrey D.: "Aerodynamic Design Opportunities for Future Supersonic Aircraft", 23rd International Congress of Aeronautical Sciences, Toronto, Canada, ICAS Paper No. 2002-871, September, 2002.

[68] Bushnell, Dennis M.: "Fluid Mechanics, Drag Reduction and Advanced Configuration Aeronautics", NASA TM-2000-210646, December, 2000

[69] Pfenninger, W., and Vermuru, C. s.: "Design Aspects of Long Range Supersonic LFC Airplanes with Highly Swept Wings", SAE Paper 881397, Aerospace Technology Conference and Exposition, Anaheim, CA, October 3-6, 1988.

[70] Wlezien, R., and Veitch, L.: "The DARPA Quiet Supersonic Platform Program", AIAA 2002-0311, 40th AIAA Aerospace Sciences Meeting & Exhibit, , Reno, NV, Jan. 14-17, 2002

[71] Komadina, Steve, and Drake, Arron: "Development of a Quiet Supersonic Aircraft with Technology Applications to Military and Civil Aircraft", AIAA 2002-0519, 40th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 14-17, 2002

[72] Spalart, P. R. and Jou, W-H., and Strelets, M. and Allmaras, S. R.: "Comments on the Feasibility of LES for Wings, and on a Hybrid RANS/LES Approach," *Advances in DNS/LES, Proceedings of the First AFOSR International Conference on DNS/LES,* Eds. Chaoqun Liu and Zhining Liu, Greyden Press, August, 1997.

[73] Vos, J. B. Rizzi, A., Darracq, D. and Hirschel, E. H.: "Navier-Stokes Solvers in European Aircraft Design," *Progress in Aerospace Sciences,* **38,** pp. 601-697, 2002.

[74] Spalart, P. R.: "Strategies for Turbulence Modeling and Simulations," *4th International Symp. on Engineering Turbulence Modelling and Measurements,* eds. W. Rodi and D. Laurence, Elsevier, May, 1999.

[75] Hedges, L., Travin, A., and Spalart, P. R.: "Detached-Eddy Simulations Over a Simplified Landing Gear," *J. Fluids Eng.* **224**, June, 2002.

[76] Mani, M. and Paynter, G. C.: "Hybrid Turbulence Models for Unsteady Simulation of Jet Flows," AIAA 2002-2959, 32nd Fluid Dynamics Conference and Exhibit, June, 2002.

[77] Batten, P., Goldberg, U. and Chakravarthy, S., "Sub-Grid Turbulence Modeling for Unsteady Flow with Acoustic Resonance," AIAA Paper No. 2000-0473, 2000.

[78] Zhang, H. L., Bachman, C. R., and Fasel, H. F.: "Application of a New Methodology for Simulations of Complex Turbulent Flows," AIAA Paper No. 2000-2535, 2000.

[79] Girimaji, S. S., Sreenivasan, R., and Jeong, E.: "Pans Turbulence Model For Seamless Transition Between RANS LES: Fixed-Point Analysis And Preliminary Results," FEDSM2003-45336, Proceedings of ASME FEDSM'03, 4-th ASME-JSME Joint Fluids Engineering Conferences, Honolulu, Hawaii, July 13-16, 2003.

[80] Nichols, R. H. and Nelson, C. C.: "Application of Hybrid RANS/LES Turbulence Models," AIAA 2003-0083, 41st Aerospace Sciences Meeting and Exhibit, Jan. 2003.

[81] Rubinstein, R., and Choudhari, M., "Stochastic Modeling of Laminar-Turbulent Transition," Proc. Of the 23rd International Council on the Aeronautical Sciences, Toronto, June, 2002.

[82] Chen, H., Succi, S., and Orszag, S., "Analysis of Subgrid Scale Turbulence Using the Boltzmann Bhatnagar-Gross-Krook Kinetic Equation," *Physical Review E*, **59**, No. 3, March, 1999.

[83] Carpenter, M. H., Singer, B. A., Yamaleev, N., Vatsa, V. N., Viken, S. A., and Atkins, H. L., "The Current Status of Unsteady CFD Approaches for Aerodynamic Flow Control," AIAA Paper No. 2002-3346, 2002.

[84] Hardin, J.C., Ristorcelli, J. R., and Tam, C. K. W., eds., *ICASE/LaRC Workshop on Benchmark Problems in Computational Aeroacoustics*, NASA CP 3300, May, 1995.

[85] Tam, C. K. W. and Hardin, J. C., eds., *Second Computational Aeroacoustics (CAA) Workshop on Benchmark Problems*, NASA CP 3352, June, 1997.

[86] Dahl, M. D., ed., *Third Computational Aeroacoustics (CAA) Workshop on Benchmark Problems*, NASA CP-2000-209790, August, 2000.

[87] Singer, B. A. and Guo, Y., "Development of CAA Tools for Airframe Noise Calculations," accepted for publication in *Intl. J. of Comp. Fluid Dyn.*, 2003.

[88] Bailly, C., Lafon, P., and Candel, S., "Computation of Noise Generation and Propagation for Free Confined Turbulent Flows," AIAA Paper No. 96-1732, 2nd AIAA/CEAS Aeroacoustics Conference, May, 1996.

[89] Bailly, C. and Juve', D., "A Stochastic Approach to Compute Subsonic Noise Using Linearized Euler's Equations," AIAA Paper No. 99-1872, 5th AIAA/CEAS Aeroacoustics Conference, May, 1999.

[90] Batten, P., Goldberg, U. and Chakravarthy, S., "Reconstructed Sub-Grid Methods for Acoustics Predictions at all Reynolds Numbers," AIAA Paper 2002-2511, 8th AIAA/CEAS Aeroacoustics Conference & Exhibit, 2002.

[91] Hunter, Craig A. and Thomas, Russell H., "Development of a Jet Noise Prediction Method for Installed Jet Configurations", AIAA Paper No. 2003-3169, 9th AIAA/CEAS Aeroacoustics Conference & Exhibit, 2002.

[92] Thilmany, J., "Probabilistic Problem Solving," *Mechanical Engineering,* Jan., 2002.

[93] Levy, D. W., Zickuhr, T., Vassberg, J., Agrawal,S., Wahls, R. A., Pirzadeh, S., and Hemsch, M. J., "Data From the First AIAA CFD Drag Prediction Workshop," AIAA Paper No. 2002-0841, 40th AIAA Aerospace Sciences Meeting and Exhibit, January 14-17, 2002.

[94] Nielsen, E. J., Lu, J., Park, M. A. and Darmofal, D. A.: "An Exact Dual Adjoint Solution Method for Turbulent Flows on Unstructured Grids," AIAA Paper No. 2003-0272, 41st AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, , January 6-9, 2003

[95] Alexandrov, N. M. and Lewis, R. N.: "An Overview of First Order Model Management for Engineering," *Optimization and Engineering*, Vol. 2, No. 4, Dec. 2001, pp. 413-430.

[96] Levy, D. W., Zickuhr, T., Vassberg, J., Agrawal,S., Wahls, R. A., Pirzadeh, S., and Hemsch, M. J., "Data From the First AIAA CFD Drag Prediction Workshop," AIAA Paper No. 2002-0841, 40th AIAA Aerospace Sciences Meeting and Exhibit, January 14-17, 2002

[97] Venditti, D. A. and Darmofal, D. L., "Adjoint Error Estimation and Grid Adaptation for Functional Outputs: Application to Quasi-One-Dimensional Flow," *Journal of Computational Physics,* **164**, pp. 204-227, 2000.

[98] Park, M. A., "Adjoint–Based, Three–Dimensional Error Prediction and Grid Adaptation," AIAA 2002–3286, August, 2002.

[99] Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V., and Hart, J. C., "The CAVE: Audio Visual Experience Automatic Virtual Environment," *Communications of the ACM,* Volume 35, Issue 6, June 1992, ACM Press, New York, NY, USA, pp. 64 - 72.

[100] Banks, D. C. and Kelley, M., "Tracking a Turbulent Spot in an Immersive Environment." Proceedings of the 1995 ACM Symposium on Interactive 3D Graphics, ACM Press, pp. 171-172, 1995.

[101] G. D. Doolen, ed., *Lattice Gas Methods for Partial Differential Equations* (Addison-Wesley, New York, 1990).

[102] L.-S. Luo, The future of lattice-gas and lattice Boltzmann methods, in *Computational*

Aerosciences in the 21st Century, M. D. Salas and W. K. Anderson, eds. (Kluwer, Dordrecht, 2000), pp. 165–187.

[103] D. H. Rothman and S. Zaleski, *Lattice-Gas Cellular Automata: Simple Models of Complex Hydrodynamics* (Cambridge University Press, Cambridge, 1997).

[104] Lockard, D. P., Luo, L-S, Milder, S. D., and Singer, B. A.: "Evaluation of PowerFLOW for Aerodynamic Applications," *Journal of Statistical Physics,* Vol. **107**, Nos. 1/2, April 2002.

[105] Shock, R. A., Mallick, S., Chen, H., Yakhot, V., and Zhang, R., "Recent Results on Two-Dimensional Airfoils Using a Lattice Boltzmann-Based Algorithm," Journal of Aircraft, Vol. 39, No. 3, May–June 2002.