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APPLIED AERODYNAMICS: CHALLENGES AND EXPECTATIONS

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Summary

Aerospace is the leading positive contributor to this country's balance of trade, derived largely from the sale of U.S. commercial aircraft around the world. This powerfully favorable economic situation is being threatened in two ways. (1) The U.S. portion of the commercial transport market is decreasing, even though the worldwide market is projected to increase substantially. (2) Expenditures are decreasing for military aircraft, which often serve as proving grounds for advanced aircraft technology. To retain a major share of the world market for commercial aircraft and continue to provide military aircraft with unsurpassed performance, the U.S. aerospace industry faces many technological challenges.

The field of applied aerodynamics is necessarily a major contributor to efforts aimed at meeting these technological challenges. A number of emerging research results that will provide new opportunities for applied aerodynamicists are discussed in this paper. Some of these have great potential for maintaining the high value of contributions from applied aerodynamics in the relatively near future. Over time, however, the value of these contributions will diminish greatly unless substantial investments continue to be made in basic and applied research efforts. The focus: to increase understanding of fluid dynamic phenomena, identify new aerodynamic concepts, and provide validated advanced technology for future aircraft.

Introduction

The United States should have a strong aeronautics program for two principal reasons: (1) aircraft sales contribute importantly to international economic competitiveness, and (2) superior aircraft are vital to a strong national defense posture. Economic competitiveness in world markets for aircraft sales requires meeting increasingly stringent environmental regulations governing aircraft noise and engine emissions, maintaining acceptable safety as the number of aircraft in the airspace system increases, and producing aircraft having competitive costs of ownership and operation. Military superiority requires aircraft with unmatched performance for both defensive and offensive operations.

Meeting these requirements in both the economic and military areas depends on a strong aeronautics program that will produce a continuing stream of technical advances in applied aerodynamics. These advances can only be derived from innovations that emerge from basic fluid dynamics and applied aerodynamics research efforts. The U.S. government has been supporting aeronautical research and technology development for over 75 years and without this government investment, continued leadership in aeronautics cannot be maintained.

The two principal reasons for conducting a strong program in aeronautical research and development will be discussed in this paper, and some related challenges for the field of applied aerodynamics will be identified. This will be followed by highlights of some emerging research that will contribute to advancing the state of the art of applied aerodynamics. In summary, the overall intent of this paper is to, first, show why it is important to the country to continue to invest in aeronautics, then to identify challenges for the discipline of applied aerodynamics, and finally to present some emerging research results that will help meet these challenges.

Economic Competitiveness and Related Applied Aerodynamics Challenges

The aerospace industry is a significant contributor to this country's economy. In 1991 it produced the largest trade surplus of any sector of our economy. Values obtained from Ref. 1 for the industry's imports, and both civil and military exports, over the past 19 years are presented in Fig. 1. These data show that trade surpluses have occurred for a number of years (with a high of $30B being reached in 1991), and that the contributions from civil

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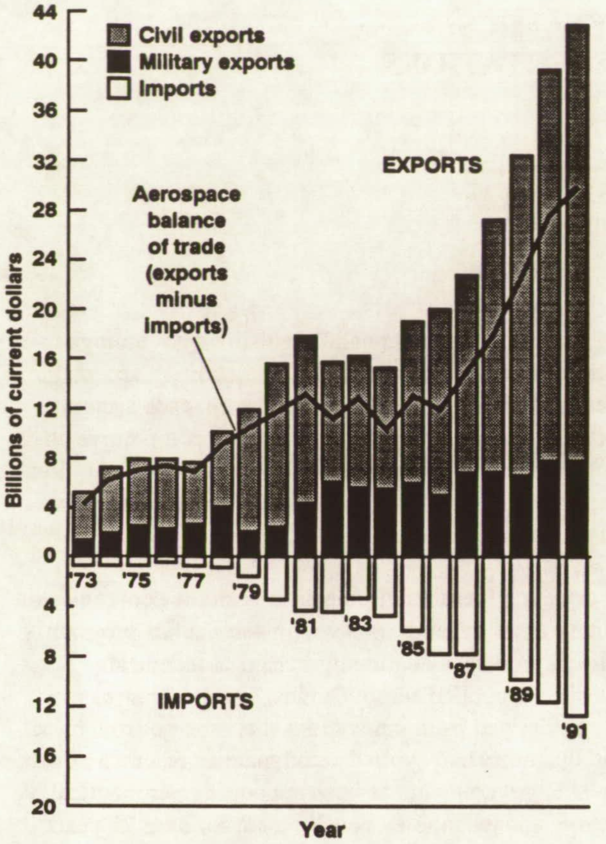

Fig. 1 Aerospace exports, imports, and trade balance.

exports have been growing steadily in recent years. It may be difficult to maintain this growth in exports relative to imports in the future because of the expected decline in expenditures for military aircraft. More than 25% of the nation's investment in research and development has been made in aerospace, and the military arena has served as the proving ground for much of the technology resulting from these expenditures. Therefore, without a strong military thrust, more of the burden for developing and validating new technology must be assumed by the civil sector if aerospace is to be maintained as a leading contributor to the nation's economy.

Despite the decline in demand for defense products, economics of the overall aerospace industry appear strong because of the very large increase in demand for new civil aircraft. There are two reasons for the increasing demand for civil aircraft. The first is the expected increase in annual revenue passenger miles (RPM). Data presented in Fig. 2 (taken from Ref. 2) show expected increases in RPMs to be 70% between 1990 and 2000; more than double by 2005; and almost triple by 2010. The second reason for the increasing demand for civil aircraft is the expected increase in retirement of older aircraft due both to age and to more stringent community noise restrictions. Up to 300 aircraft each year are expected to be retired through the year 2000, and 150 each year from 2001 to 2010. In contrast, only 91 aircraft were retired from commercial airline service in 1991. The net result of these forecasts is that deliveries of new aircraft will average about 600 each year through the year 2010.

A concern, however, is the continuing erosion of the worldwide market share enjoyed by the U.S. manufacturers of commercial aircraft. There are, of course, many reasons for this decline in market share. One is that other countries continue to make substantial investments in aeronautical research and development and now offer products that are technically competitive. Another is the sometimes-lower cost of ownership of foreign aircraft made possible by lower prices due either to lower production costs or to more favorable product financing. Additional loss in market share would have a severe impact on the economy, especially if market projections for future commercial aircraft are realized. Capturing an important segment of the expected future market will most likely require development of a new supersonic transport, provided current studies confirm environmental acceptability. This implies an even greater investment in new technology than would be required to meet the challenges associated with a wholly subsonic transport market.

This country originally gained preeminence in aeronautics and the dominant share of the commercial aircraft market for two reasons. One was early recognition of the importance of aeronautics, and the second was the government commitment to sustain investment in research and development. This commitment has existed over the past 75 years, beginning with the creation of the National Advisory Committee for Aeronautics (NACA) in 1915. Halting this erosion of market share will require continued substantial investments to find cost effective technical improvements that meet increasingly stringent demands on performance and environmental compatibility.

Investment made by government through the NACA (and now NASA), and by industry is augmented by that made by the Department of Defense (DOD). Much of the aeronautical technology developed with DOD funds over the years also has been useful to the civil sector. Therefore, any reductions of DOD investments in aeronautical technology must be compensated through greater investments by industry and by government through NASA. Finally, if a product is not less expensive than competing products, it must be technically superior and clearly satisfy user requirements to compete in the world marketplace.

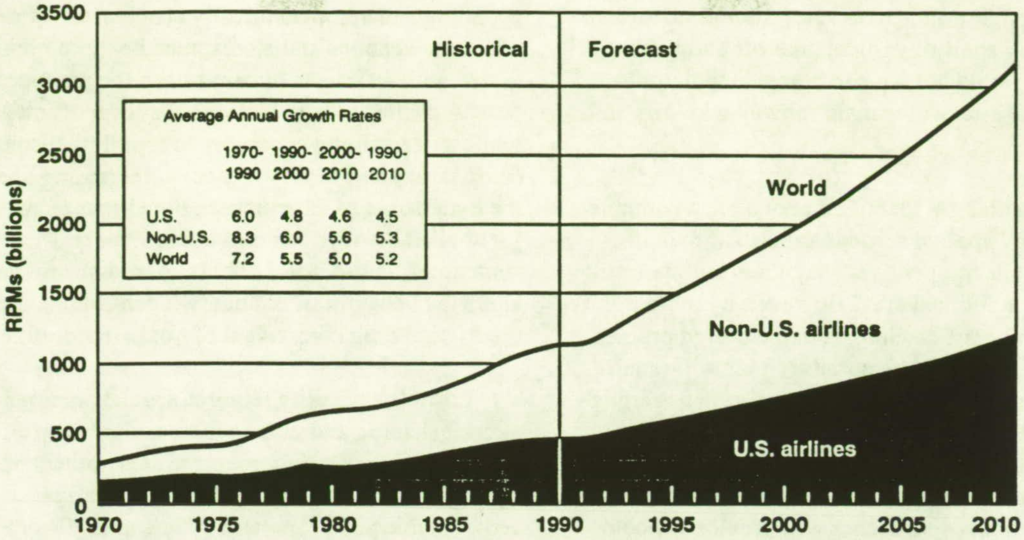

Fig. 2 World revenue passenger miles, past and future.

Advances in the field of applied aerodynamics are crucial to both maintenance and improvement of economic competitiveness. Some elements contributing to the economics of an aircraft that can be affected by applied aerodynamics are pricing, direct operating costs, environmental compliance, and safety.

Competitive pricing of aircraft depends, in part, on manufacturing costs, which are influenced by the degree of design complexity. This challenges the applied aerodynamicist to find simpler designs to manufacture. For example, simpler high-lift devices to perform the functions of the sometimes quite mechanically complicated wing leading- and trailing-edge devices. Also, minimizing the number of aerodynamic surfaces and keeping them simple, both geometrically and mechanically, will help to reduce manufacturing costs.

Direct operating costs are strongly influenced by the amounts of fuel and time required to perform a given mission with a given payload. Fuel required can be minimized by maximizing the Breguet range factor. This calls for maximizing the product of cruise Mach number and lift-to-drag ratio, divided by the engine efficiency expressed in pounds of fuel per pound of thrust per hour. Challenges for applied aerodynamicists are to maximize aircraft drag-rise Mach number and lift-to-drag ratio (including the installed and operating engines), and to work with the propulsion engineers to find more efficient engine inlet, nozzle, compressor, turbine, and combustion chamber designs.

Environmental compliance is largely influenced by engine emissions, and both engine and airframe noise. Engine emissions can be made more acceptable by improving ways of mixing fuel and air in engine combustion chambers. Also, adverse consequences of emissions on the Earth's ozone layer can be minimized by designing aircraft that will cruise efficiently at the desired Mach number, at altitudes not much higher than 50,000 feet. Reduction of engine noise involves design of low-noise combustion chambers, light weight exhaust-noise suppression devices, and inlet and compressor designs to minimize compressor noise. Noise can also be minimized at communities surrounding airports through development of aircraft with very high lift at take-off and landing speeds. This would both keep the high-noise footprint on the community as small as possible and permit operations at lowest possible levels of thrust (low exhaust velocities). The challenge to reduce airframe noise throughout the flight envelope calls for minimizing turbulent flow and the regions of separated flow over the aircraft.

Safety can be influenced by applied aerodynamicists in several ways. As aircraft become larger and faster, landing and take-off speeds have a tendency to increase. This must be overcome by designs having high lift capability at low speeds. More and more people traveling by air, and the very high cost of constructing new airports, are both causing the number of airport operations to reach safety limits. Some of this congestion can be relieved by designing new aircraft that can carry substantially greater numbers of passengers. Additional relief can be obtained by finding ways to reduce unfavorable effects of trailing wake vortices from a leading aircraft on another aircraft following closely. If this can be done, spacing between aircraft can be reduced safely so that the number of operations handled by an airport can be increased. Still another way to relieve congestion is to develop short-haul aircraft, having either very short or vertical take-off and landing capabilities that would not have to compete with long-haul conventional aircraft for main runway take-offs and landings.

All of the challenges identified above must continue to be addressed by applied aerodynamicists if manufacturers are to remain competitive. Major advances are still possible in each individual area. However, by more tightly integrating a number of disciplines in the design process, even greater advances will be possible. This will require simultaneous consideration of disciplines such as aerodynamics, structures, propulsion, and active controls. Applied aerodynamicists probably should take the lead in forcing this increased integration. In each individual discipline, computational approaches will provide the common interfaces necessary to make all of this possible.

Military Superiority and Related Applied Aerodynamics Challenges

National defense has become increasingly dependent on capabilities to conduct air warfare and to move large quantities of people and materiel long distances in short periods of time. Maintaining superior capabilities in both of these areas requires continuing development of all types of aircraft including air-to-air and air-to-ground fighters, strategic bombers, conventional transports, short take-off and landing transports and fighters, manned and unmanned reconnaissance aircraft, and rescue aircraft.

Most elements discussed earlier that contribute to the economics of commercial aircraft also apply to military aircraft. Additional elements, either primarily associated with military aircraft or requiring additional emphasis, are: maneuverability, agility, speed, low observability, and service altitude ceiling.

Maneuverability and agility call for removing restrictions on the attitudes in which an aircraft can routinely operate. One challenge is to make fighter aircraft stable and controllable at all angles of attack and for reasonably large ranges of sideslip. Another is to provide the capability to develop side forces without introducing yaw. Still another is to maintain the capability to develop high pitch and roll rates in any attitude. These challenges require new ways to control an aircraft, either solely through aerodynamic means or through combinations of aerodynamic and propulsive means.

Sustained flight of an aircraft at very high speeds obviously requires high-thrust engines with good fuel economy and aerodynamically efficient airframes. In addition, weapons and stores must be more highly integrated with airframes than has been the practice in the past. A challenge is to increase the level of integration while still retaining capability to rapidly jettison stores (drop tanks) and deploy weapons. Increasing speed into the hypersonic Mach number range imposes requirements for applied aerodynamicists to consider real-gas and, sometimes, low-density effects. Aerodynamic heating also alters the behavior of boundary layers and, consequently, the friction drag component of total aircraft drag.

Low observability requires special attention to both aircraft shaping and noise suppression. It is well known that this imposes requirements to seek radical new ways to shape an aircraft while still maintaining reasonable aerodynamic and propulsive efficiencies. Over the years, applied aerodynamicists have developed many empirical factors for designing conventional aerodynamic shapes. These can no longer be used. In fact, aerodynamics can no longer be considered independent of electromagnetics considerations. Rather, both of these disciplines, as well as materials considerations, must be treated simultaneously in the design process.

Extremely high-altitude subsonic flight poses another challenge: designing an aircraft with very low wing loading that is also manageable in gusty weather at low altitudes, particularly during take-off and landing.

Emerging Research Results and Their Implications for Applied Aerodynamics

Emerging research results within this decade will contribute greatly to meeting many of the challenges for maintaining economic competitiveness and military superiority. Since many of these results derive from computational approaches, a brief description of equations governing aerodynamic behavior is given.

Equations for Aerodynamic Behavior

The Navier-Stokes equations describe behavior of fluids in the continuum flow regime. These equations were derived over 100 years ago and now they can be solved, without approximation, for flows about complex three-dimensional aerodynamic shapes. However, results of estimates presented in Ref. 3 show that computer requirements are now excessive and probably will be for many years to come. Fortunately, approximate forms of the equations have been developed that can yield excellent predictions of aerodynamic behavior for many engineering applications.

Five different levels, ranging from the most complex full equations to the simplest approximate form, are: (1) full Navier-Stokes or direct simulation (DS), (2) large eddy simulation (LES), (3) Reynolds-averaged Navier-Stokes (RANS), (4) nonlinear inviscid, and (5) linear inviscid. Solutions to most problems of current interest in aerodynamic analysis require consideration of viscous effects. So considerable future attention will likely be placed on either the full Navier-Stokes or the LES equations for benchmark research studies, and on either the LES or the RANS equations for practical applications. Brief descriptions of the LES and RANS approximations follow.

In the LES approximation, large-scale turbulent eddies that can be resolved by the computational grid are calculated directly, and only not-resolvable small-scale motions are modeled. The premise of LES is that large-scale motions carry most of the energy contained in the flow, and essential characteristics of turbulence dynamics can be captured from these large scales alone. Only the small scales of turbulence, which are presumably more isotropic and universal in character, are modeled.

The RANS form of the governing equations neglects no terms in the full equations but all scales of turbulence momentum, energy, and heat transport are modeled. Many different problems are now being solved with these equations by using currently available supercomputers. Computing times range from several minutes to tens of hours, depending upon complexities of geometries and flow physics. Unfortunately, no "universal" turbulence model seems to reproduce "true" flow physics in all situations. Some models provide excellent results for well-behaved attached flows that are everywhere either laminar or turbulent. However, none can adequately model transition from laminar to turbulent flow, and few can satisfactorily handle separating and reattaching flows without empirical adjustments being made to the turbulence model. Example results obtained using the full Navier-Stokes, LES, and RANS equations are presented later in this paper. Additional details of these approximations can be found in Ref. 4.

These equations are instrumental in the following 13 research areas.

Boundary Layer Transition

It is difficult to accurately determine the true performance of an aircraft before it is actually built and flown. One contributing factor is uncertainty in the location of boundary layer transition from laminar to turbulent flow on the various aerodynamic surfaces. Two factors that contribute to variations of transition location between wind tunnel and flight measurements are Reynolds number and freestream turbulence. Tests of subscale models in wind tunnels generally cannot duplicate true flight Reynolds numbers, and wind tunnel freestream turbulence is usually higher than that in free air.

It is possible to calculate the location of transition from first principles by solving the full Navier-Stokes equations. Previously, this had been done only for very low Reynolds-number flows, particular geometries, and non-arbitrary upstream and downstream flow boundary conditions. All of these were dictated by limitations in computer speed and memory.

Recently, the numerical method described in Ref. 5 was developed to treat general geometries and arbitrary flow boundary conditions with computers now available. Initial results for the skin friction along the length of a flat plate are shown in Fig. 3. They are compared with measurements made in two different investigations (reported in Refs. 6 and 7), as well as with skin friction distributions from laminar-flow theory and from a correlation (presented in Ref. 8) of measurements from numerous turbulent flows. Flow Mach and Reynolds numbers at the leading edge of the plate were 0.1 and 50,000/in., respectively. Freestream turbulence intensity level at the plate leading edge is about 2.75% for both computation and experiments. The computed results lie between the two sets of measured data. Computing time required to obtain the results in Fig. 3 was 400 hours on a Cray-YMP processor. At the very low Mach number of 0.1 for this case, the large difference between fluid velocity and speed of sound results in an extremely slow numerical integration process. More recent work shows that for Mach numbers higher than about 0.4, computing time will only be about 25% of that required for this case.

Clearly, it still is not practical to solve the full Navier-Stokes equations for flows about arbitrary configurations at Reynolds numbers of most interest. Nevertheless, a method now exists for providing benchmark results for all of the properties of flows undergoing transition, including heat transfer, and for arbitrary geometries. Furthermore, this method can be used to search for ways to control the transition process. Having this computational capability should greatly accelerate the

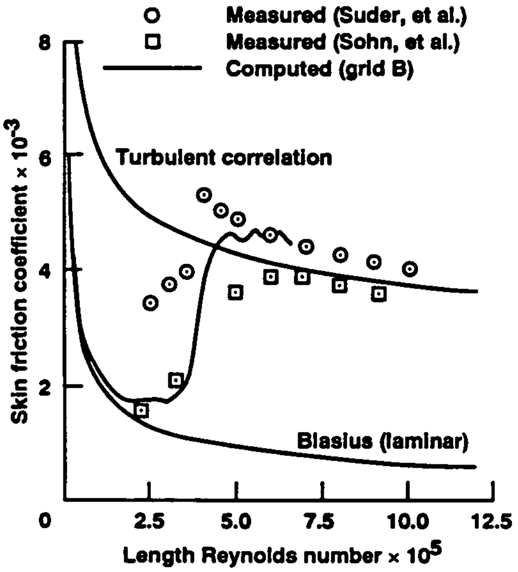

Fig. 3 Measured and computed skin friction coefficient along the length of a flat plate.

search for better models to use in approximate predictive methods for the transition process. Finally, this capability provides an approach for calculating flows about arbitrary geometries using either full Navier-Stokes equations or the more computationally efficient Large Eddy Simulation approximation.

Turbulence Modeling

Another major advance related to predicting viscous compressible flows is the development of a new dynamic subgrid-scale model, reported in Ref. 9, for use with the LES approximation. This model appears to have overcome all deficiencies of the widely used Smagorinsky model. The new model utilizes strain rate fields at two different scales in the computed large-scale field to extrapolate the small-scale stresses in the unresolved subgrid-scale region. This avoids the need to choose a different optimal constant for each flow being computed. That is, the closure "constant" is determined as part of the calculation of each flow and it is allowed to vary with local flow conditions. In addition, the model has the correct limiting behavior near walls: it vanishes in laminar flow, it properly represents dissipation and backscatter of energy from small scales to large scales in the laminar-to-turbulent transition region, and it includes compressibility effects. Comparisons presented in Ref. 9 show excellent agreement for various turbulence quantities (obtained using the dynamic subgrid-scale model and the LES equations) with solutions of the full Navier-Stokes equations.

This advance, together with the ones discussed earlier in connection with the prediction of boundary layer transition, has set the stage. For the first time, with the LES approximation, flows about aerodynamic shapes are calculated without use of pre-selected modeling "constants" either for the transition process or for the fully-developed turbulence. As computers become more powerful, these advances could have profound implications for computing aerodynamic characteristics of complete aircraft. It will be possible to calculate laminar, transitional, and turbulent flows as well as attached, separating, and reattaching flows about arbitrary shapes. This will be done without empiricism and with accuracy closely approaching that provided by the full Navier-Stokes equations. Flows about jet engine turbine and compressor blades at full-scale Reynolds numbers now can be attempted with today's computers. In fact, such efforts already have begun.

Turbines and Compressors

Remarkable advances in jet engine performance have been made over the years, despite the complexity of compact, multiple-stage compressors and turbines. Traditionally, the design process has relied heavily upon empirical correlations developed from data bases provided by previous designs. Despite the maturity of engine technology, considerable improvements are still possible, as shown by the study reported in Ref. 10. These improvements would be accelerated by availability of more general and reliable predictive capabilities for time-dependent viscous flows through multiple-stage, axial-flow compressors and turbines. Advanced designs that employ high blade-loadings and small axial gaps between blade rows preclude the use of previous methods of analysis that were based on isolated airfoil rows. Fortunately, new numerical methods that treat multiple rows of rotor and stator blades as a system are being developed rapidly.

One emerging method, based on the Reynolds-averaged Navier-Stokes equations, is an extension of earlier work (presented in Ref. 11) in which the flow through a single-stage turbine configuration was simulated numerically. Initial results from this new method, for the flow through a 2-1/2-stage two-dimensional compressor, are presented in Ref. 12. Sample results from this work are presented in Fig. 4, where calculated time-averaged pressure coefficients for the second stage rotor and stator are compared with measurements made on a three-dimensional model. Agreement between two-dimensional calculated results and midspan results from the three-dimensional test is quite good. This numerical work is being extended to three dimensions, and preliminary results for

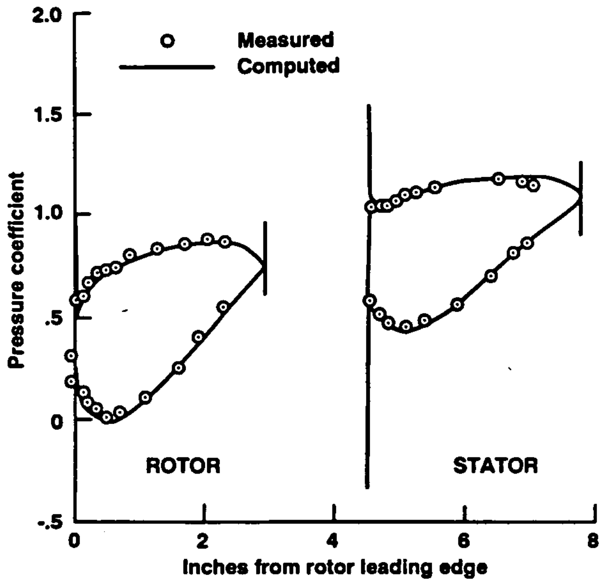

Fig. 4 Calculated and measured instantaneous surface pressures on the blades of a 2-1/2-stage compressor.

instantaneous surface pressures on the blades of a 2-1/2-stage compressor are shown in Fig. 5 (see color page).

Clearly, these calculations are expensive to make with today's computers. However, the expected availability, before the turn of the next century, of at least an additional three orders of magnitude of machine processing power will bring this technology into the hands of designers.

High Lift Devices

High lift devices are important features of both military and civil aircraft. They enable heavily loaded aircraft to take off from runways of reasonable length and to maintain controlled flight during landing approaches at reasonably low speeds. Their use also controls the size of the high-noise footprint in the vicinity of airports by enabling aircraft to gain altitude quickly. This latter capability is particularly important for next-generation supersonic transports that must be able to operate from existing commercial airports without benefit of very high bypass ratio engines that are inherently quieter. Two recent technical advances will be presented to illustrate progress being made in this important area. The first is a very efficient and accurate computational method for predicting flows about multi-element airfoils, and the second is a very simple miniature split flap that has a remarkable capability to increase airfoil lift.

Computation of flows about multi-element airfoils is a particularly challenging problem. In addition to geometric complexity, treatment of this problem requires consideration of boundary layer separation, boundary layer and wake interaction, and Reynolds-number effects. A very efficient method for treating these complexities was reported recently in Ref. 13. Results obtained by solving the incompressible Reynolds-averaged Navier-Stokes equations, for both single and multi-element airfoils, are presented in the reference. An example of these numerical results, compared with measurements, is presented in Fig. 6 for a NASA 9.3% thick blunt-based supercritical airfoil at 14.25° angle of attack, with a leading edge slat deployed –47.2° and two trailing edge flaps deflected to 30 and 49.7°, respectively. Chord Reynolds number is 2.83 million and the measured results were obtained at a Mach number of 0.201. Agreement between computed and measured results is excellent, and the computation required only about 4 min on a single Cray-YMP processor. When methods similar to this one are extended to treat three-dimensional multi-element wings in the near future, it should be possible to accelerate development of new and less complicated high lift devices.

A new high lift device now under study at the NASA Ames Research Center shows remarkable potential. It is similar to the Gurney Flap used in automobile racing, but it has the distinguishing feature of being split so that it may be located upstream of the airfoil trailing edge. Unpublished computed and measured results for a 1.25% chord flap located at the trailing edge of a NACA 4412 airfoil are shown in Fig. 7. Results are for a Reynolds

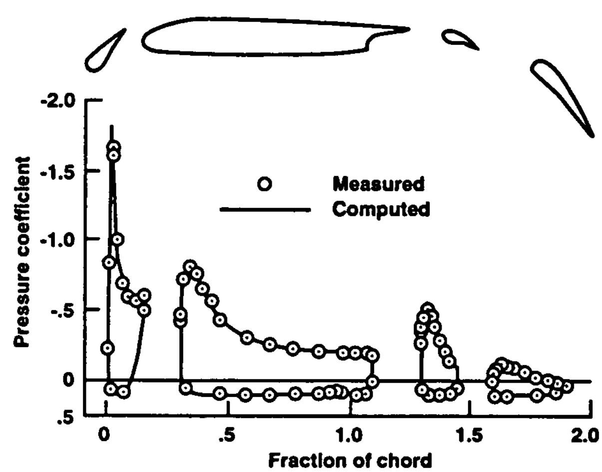

Fig. 6 Surface pressure coefficients for a four-element NASA 9.3% thick blunt-based supercritical airfoil. Leading edge slat at –47.2°; trailing edge flaps at 30° and 49.7°, respectively; Mach number = 0.201; angle of attack = 14.25°.

number of 4 million. The computed results were obtained from an incompressible Navier-Stokes code, and the measured results are for a very low subsonic Mach number. The miniature split flap is quite effective in increasing the lift throughout the angle of attack range, and it increases maximum lift of the airfoil by about 20%. The flap produces a lift increment by reducing the extent of upper surface trailing edge flow separation while increasing downward deflection of the flow as it leaves the trailing edge. Parametric studies are being performed to investigate different flap lengths and hinge-line locations.

These examples provide an optimistic outlook for future advances in the development of high lift devices of greater simplicity with attendant manufacturing and maintenance cost reductions.

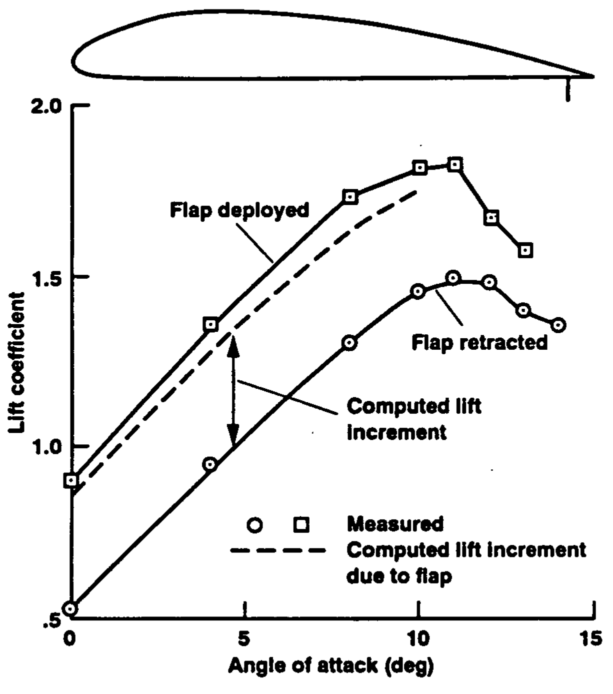

Fig. 7 Effect of 1.25% chord miniature split flap on the variation of lift coefficient with angle of attack for a NACA 4412 airfoil.

High Angle of Attack Technology

NASA's High Alpha Technology Program is providing a greater understanding of the physics of massively separated flows and vortex bursting, new tools for use in designing future highly maneuverable aircraft, and new concepts for controlling aircraft at all possible attitudes. The program includes numerical analysis, wind tunnel experiments with both sub-scale and full-scale models, flight simulator studies of new control laws for extreme attitude flight with thrust vectoring, and final validation using an F-18 testbed aircraft.

Flow about a complete, complex geometry aircraft, at angles of attack where flow physics also are very complex, now can be calculated with sufficient precision to be of practical use in the design process. An example of this capability is shown in Fig. 8. There, pressure coefficients calculated by solving the Reynolds-averaged Navier-Stokes equations are compared with flight measurements made at two stations on the F-18 high angle of attack research vehicle, flying at Mach number 0.243 and at 30.3° angle of attack. Inboard and outboard leading edge flaps are deflected 33° nose down, and the horizontal tail is deflected 7° nose down. Remarkable agreement between calculated and measured results is noted. Additional results, and a more complete discussion of the computational procedures, are presented in Ref. 14.

Performing numerical calculations with the time-accurate version of the code provides time varying pressure loads resulting from unsteady separated flow. Coupling computed unsteady pressure loads with a structural response code permits the study of buffet phenomena. Having this capability is very important, since vertical tail buffeting is common on twin tail aircraft flying at high angles of attack and can be severe enough to cause premature structural fatigue. Example results from Ref. 15, for one of the vertical tails on the F-18 experiencing buffeting, are presented in Fig. 9. Here the calculated buffet frequency is correlated with buffet frequencies measured on two different size wind tunnel models and on the F-18 in flight. It is noted that all of the results show reasonably good correlation.

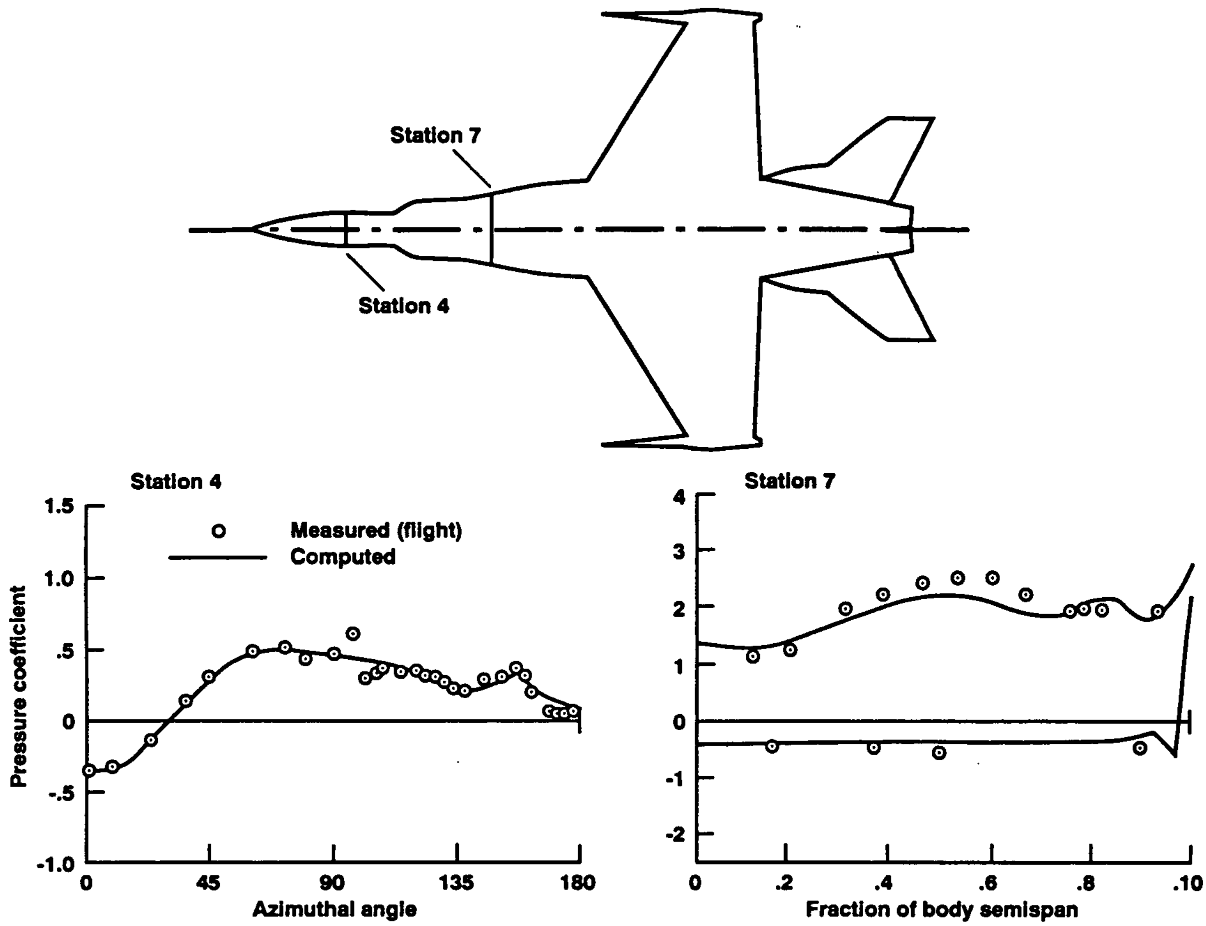

Fig. 8 Comparison of computed surface pressure coefficients with those measured in flight. Leading edge flaps 33° nose down; horizontal tail 7° nose down; Mach number = 0.243; angle of attack = 30.3°.

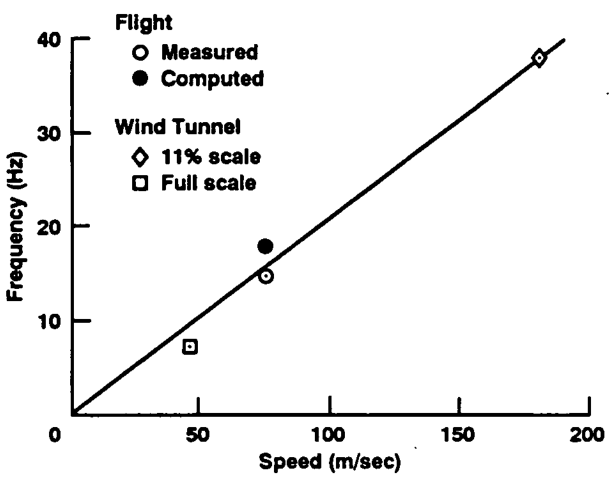

Fig. 9 Computed and measured F-18 vertical tail buffet frequency. Mach number = 0.24; angle of attack = 30°; Reynolds number based on chord = 11 × 10^6.

Calculations of this type, that include both complex geometries and complex physics, require about 55 hr on a Cray-YMP processor for a single case. Improvements in numerical methodology, and availability of more powerful computers, should bring this time down to the order of minutes before the turn of the next century. Thus, applied aerodynamicists can expect to routinely use this capability for aircraft design in the not-too-distant future.

Powered Lift

Computational tools available to assist designers of powered lift vehicles have been quite limited. It is even difficult to obtain from tests of scale models in wind tunnels reliable quantitative aerodynamic performance data for lift-off and hover in ground effect, and for transition from vertical to horizontal flight. This is because of scaling effects sensitive to Reynolds number. On the other hand, full-scale testing of a large number of new concepts is not practical early in design cycles because of cost considerations. Furthermore, previously available computational methods for inviscid flows, even with corrections for viscous boundary layers, have proved inadequate. However, recent advances in supercomputer and algorithm capabilities now allow attempts to solve the three-dimensional Reynolds-averaged Navier-Stokes equations for flows about powered lift vehicles.

Efforts are under way to calculate the flow about a complete AV-8B Harrier and to validate the results by comparisons with data obtained from flights of a YAV-8B V/STOL research aircraft. Early results from this effort are presented in Ref. 16. An example of the complexity of the flow surrounding the Harrier flying at 8° angle of attack 30 feet above the ground, with a forward Mach number of 0.04 is shown in Fig. 10 (see color page). There, calculated instantaneous streamlines are shown for only a portion of the entire flowfield. In addition to providing instantaneous aerodynamic loads, lift, drag, pitching moments, and knowledge of whether or not hot gases are being ingested into the inlets, the computational method also can provide valuable information about "suckdown" in ground effect. This latter information can be obtained by performing calculations with and without engines operating and then comparing the results. In this example, without the wing flaps deflected, calculations predicted a net loss of about 17%of the engine thrust due to "suckdown" effects.

Dedicated flight tests of the YAV-8B are planned to validate this new computational capability, and one experiment already has been performed. In it, the possibility was investigated of using infrared imagery as a nonintrusive method for providing qualitative data for jet trajectories and major flow structures around the vehicle. An example of initial results taken from Ref. 16 is shown in Fig. 11 (see color page). Infrared measurements made during a flight of the YAV-8B are compared with calculations. Note that outflow from the rear jets only may be visualized with this technique since the temperature of fan air flow emanating from the front jets is not hot enough to produce an infrared image. Further work is planned to quantify information provided by this technique.

Calculation of flows about powered lift vehicles is computationally expensive at this time. Results discussed above now require about 40 hr of calculation on a Cray-YMP processor. Of course, this time is expected to be reduced to a matter of minutes before the end of the decade through improvements in algorithms and computers. At that time, applied aerodynamicists can use this new capability to greatly improve performance and efficiency of powered lift vehicles.

Aeroacoustics

Commercial aircraft are facing increasingly strict regulations governing noise in the vicinity of airports. Achieving jet noise suppression without incurring unacceptable penalties in thrust loss, cost, and weight will be an increasingly difficult challenge. Even for military aircraft, jet noise is becoming more of a concern. More powerful and more highly integrated engines are exacerbating airframe component fatigue due to jet noise, and previously mentioned performance penalties result from the use of noise suppression devices. Lack of adequate methods for predicting source noise, and its propagation to the far field, have hampered progress in finding solutions to these problems. Recent important advances have been made, however, in the development of computational methods for predicting sound pressure levels in both the near and far fields. These offer the hope of providing new analysis tools to assist in developing and evaluating suppression concepts.

The results of a study presented in Ref. 17 show one advance in which the far field sound from a pair of compressible co-rotating vortices is calculated. Sound pressure levels obtained from solutions of the full Navier-Stokes equations were found to agree within 3% with estimates made using acoustic theory for this two-dimensional problem. This result is very impressive. However, integration of the full three-dimensional Navier-Stokes equations into the far field for high Reynolds number flows and complex surface boundaries would involve excessive computational cost at this time.

Results of another recent study reported in Ref. 18 offer a possible approach for making computational aeroacoustics affordable sooner. This optimism is predicated on development of an accurate finite difference method for calculating acoustic waves. This would provide a unifying approach for connecting near field noise source predictions made with finite difference methods with the acoustic field equations governing the far field. A fourth order finite difference algorithm that maintains integrity of phase correlated waves over long distances is derived in the reference work. In addition, the method allows waves to freely radiate beyond mesh boundaries. Essentially first principle predictions of aircraft jet noise in the far field should now be possible. Inner boundary conditions for this acoustic propagation method would need to be obtained from time-accurate near field Navier-Stokes solutions like the method described above for the source noise. Having such a computational approach should hasten development of improved noise suppression techniques.

Rotorcraft

Aerodynamic flows about rotorcraft are extremely complicated. These flows, even for low speed or hover conditions, are mathematically nonlinear, three-dimensional, and unsteady, and have regions of transonic flow near blade tips. Wakes shed from rotating blades are complex vortical flows that may interact with other blades and the fuselage. All of these complications have made it very difficult to develop suitable predictive methods for use in design of rotorcraft.

Until recently, application of computational fluid dynamics methods has been limited to isolated components of complete vehicles. However, aerodynamic interactions between rotating and nonrotating components are widely recognized as major challenges that must be addressed before computations can be a major contributor to the design process. This is discussed more fully in Ref. 19. Measured progress has been slow, consisting mostly of conceptualization and development of viable strategies for interfacing different computational grid structures. One such method is described in Ref. 19. It defines a computational domain about an arbitrary body in which the rotor is represented by an actuator disk. A Navier-Stokes technique that admits a prescribed pressure jump across the actuator disk is then applied. This simplified representation of rotor blades will be replaced by a more accurate finite-difference simulation when computing power permits. In the meantime, this method can be used to study effects of the rotor wake on nearby fuselage or wing components.

Tiltrotor designs offer many opportunities for increased rotorcraft performance for both civil and military applications. Tiltrotor aircraft can take off and land vertically, and fly at more than twice the speed of conventional helicopters. In the civil commuter application, vertiports can be placed either at downtown metropolitan locations or at remote small towns. Passengers can be transported at high speed either to downtown locations in other cities several hundred miles away, or to hub airports where these aircraft would not have to compete for use of already overcrowded main airport runways.

A significant challenge in the design of tiltrotor configurations results from the wing being immersed in the rotor wake during hover. This produces a download on the wing which reduces its lifting effectiveness during take-off and landing. The result is a reduction in payload that can be carried. Complete analysis of this situation requires calculation of complex three-dimensional flows about a wing at –90° incidence.

An initial attempt at this problem is presented in Ref. 20. The two-dimensional download flow field is calculated by solving the velocity-vorticity formulation using a staggered-grid approach in a fully coupled manner. In this method, vorticity is defined at mesh nodes, and velocity components are defined at mesh-cell sides. This arrangement allows for accurate representation of the definition of vorticity at node points and for conservation of mass at cell centers. Additionally, the fully coupled method provides for use of an implicit method that requires only a single iteration to converge at each time step. A comparison of calculated and measured pressure distributions on the XV-15 airfoil is shown in Fig. 12. The negative pressure peak is accurately predicted in location but underpredicted in absolute value. Calculated lower-surface pressures are in excellent agreement with measured results.

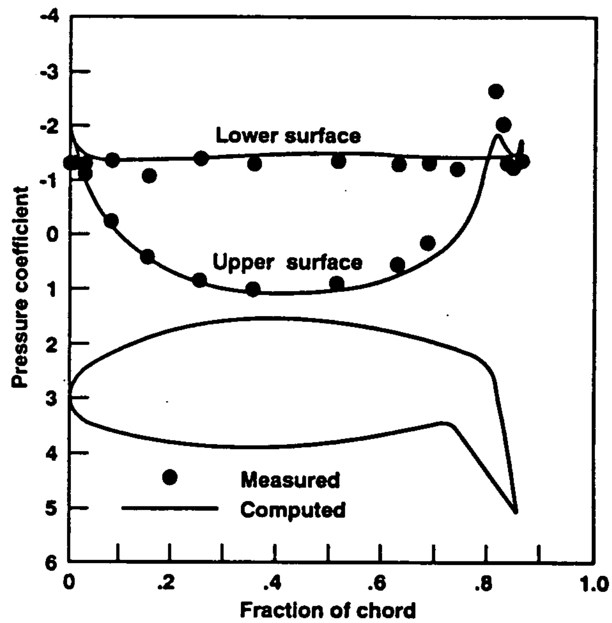

Fig. 12 Comparison of calculated and measured average surface pressure coefficients on the XV-15 airfoil; flap deflection = 60°.

Although computational methods for predicting rotorcraft aerodynamics have progressed significantly in recent years, an accurate finite-difference simulation of complete flow fields about these vehicles still is not feasible. Limitations exist in many areas including computer power, algorithms, grid generation, turbulence models, and wake simulations. However, the technical challenges are being addressed and eventually will be met.

Oblique Wing

Substantial improvements in both performance and efficiency can be realized by abandoning the notion that aircraft must possess bilateral symmetry. A number of years ago, R. T. Jones presented analyses in Refs. 21 and 22 showing the optimum wing, for both supersonic and high subsonic Mach numbers, to be one that pivoted about its centerline with one tip pointing forward and the other tip pointing aft. The pivot angle, or sweep, can be varied with Mach number such that the component of Mach number normal to the leading edge always is as close to the optimum as possible. Since the theories were published, aerodynamic advantages have been validated by wind tunnel tests of various wing-body combinations having obliquely swept wings. Feasibility also has been demonstrated in flights of both manned and unmanned aircraft.

Interest in development of a second-generation supersonic transport has prompted new studies of the oblique wing concept. Now flying wings are no longer an oddity, electronic stabilization of aircraft is a reality, and very large aircraft are required to satisfy traffic demand. So an oblique all-wing aircraft is more attractive than ever before. The oblique flying wing theoretically has maximum aerodynamic performance over a broad range of Mach numbers (both subsonic and supersonic). In addition, it has theoretical maximum structural efficiency, can easily meet the FAR-36 Stage III noise standards and (studies show) it might be able to perform the mission of a 747-400 aircraft at twice the speed and about the same cost. Aerodynamic efficiency is illustrated in Fig. 13. The estimated variation of lift-to-drag ratio with Mach number of an oblique all-wing transport is compared to that for a more conventional delta wing design. The oblique wing

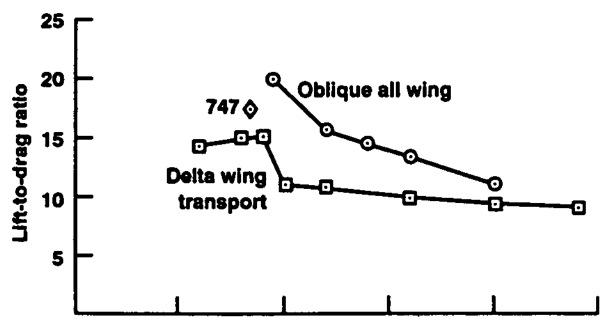

Fig. 13 Calculated variations of lift-to-drag ratio with Mach number for a delta wing supersonic transport, an oblique all-wing transport, and a 747-400 transport.

lift-to-drag ratio is considerably greater than that for the delta wing throughout the Mach number range and even exceeds the lift-to-drag ratio for a conventional transport at high subsonic speeds.

Considerable additional work still is required to resolve human factors issues associated with asymmetric aircraft, handling qualities and control laws, engine installation issues, landing gear arrangements, and a number of other technological uncertainties. Nevertheless, there are no known technology roadblocks to the development of an oblique all-wing aircraft.

Hypersonics

Advent of the National Aerospace Plane Program (NASP) stimulated renewed interest in development of technology for hypersonic flight. The goal of the NASP is to demonstrate, with the X-30 research vehicle, the capability to take off from a conventional runway and fly to nearly orbital speeds using airbreathing propulsion. This is an extremely challenging task since there are no ground-based test facilities that can closely match the complete flight environment at Mach numbers above about 8.

The last aircraft-like vehicle that this country developed for flight from orbital to landing speeds is the Space Shuttle orbiter. That task was somewhat simpler than the one facing the developers of the X-30 since the orbiter is boosted to orbit by rocket engines and is unpowered during reentry. Nevertheless, it was very difficult, and measurements made during orbiter flights have shown where improvements are needed in tools for designing hypersonic vehicles.

One such area needing improvement is that involving the determination of aerodynamic characteristics of vehicles flying at very high speeds where the airflow about the vehicle does not behave as a perfect gas. This is illustrated by results presented in Fig. 14, in which the predicted center of pressure location on the orbiter is compared with measurements made during pullup/pushover maneuvers on the flight of STS-2 at Mach number 21. These results were obtained from Ref. 23. Note that preflight predictions based on wind tunnel data determined the center of pressure to be between 0.6 and 0.8% of the orbiter body length more aft than the location measured in flight. Fortunately, sufficient trim power provided by the body flap was available to compensate for this large unexpected difference between predicted and actual center of pressure locations. Subsequent analysis attributed this large

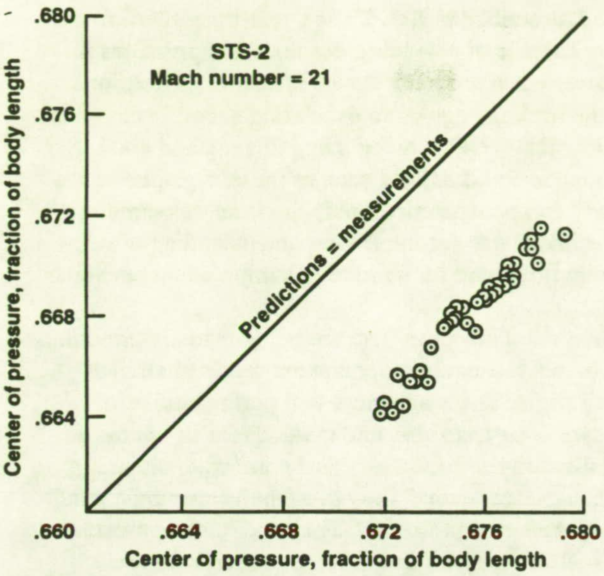

Fig. 14 Comparison of shuttle orbiter longitudinal center of pressure measured in flight, with predictions based on wind tunnel data for pullup/pushover maneuvers.

difference to real gas effects which were not adequately known when the vehicle was designed.

Improvements in understanding how to account for real gas effects have been made since the design of the orbiter. In addition, today's more powerful computers permit calculations including these complex physics to be made with a reasonable amount of computer time. An example of effects of real gas environments on aerodynamic characteristics of an airfoil, with a chord length corresponding to that at the mid semispan location of the shuttle orbiter wing, is shown in Fig. 15. Real gas reacting flow chemistry was calculated with a code that accounts for both thermal and chemical nonequilibria in the shock layer. Also shown for comparison are results calculated by assuming perfect gas behavior (constant ratio of specific heats). Lift and drag coefficients are not strongly affected by real gas considerations. However, center of pressure location from the real gas calculation is more than 1% of chord forward of the location based on the perfect gas estimate. This forward shift is consistent with that found in the studies of shuttle orbiter aerodynamics. These results are discussed in more detail in Ref. 24.

Accurate computational methods for hypersonic flows are a necessity because of the lack of ground-based test facilities capable of reproducing real gas environments. Applied aerodynamicists must rely extensively on the computer to design the X-30 vehicle. Accordingly, considerable emphasis is currently being placed on developing and validating methods for calculating flows about

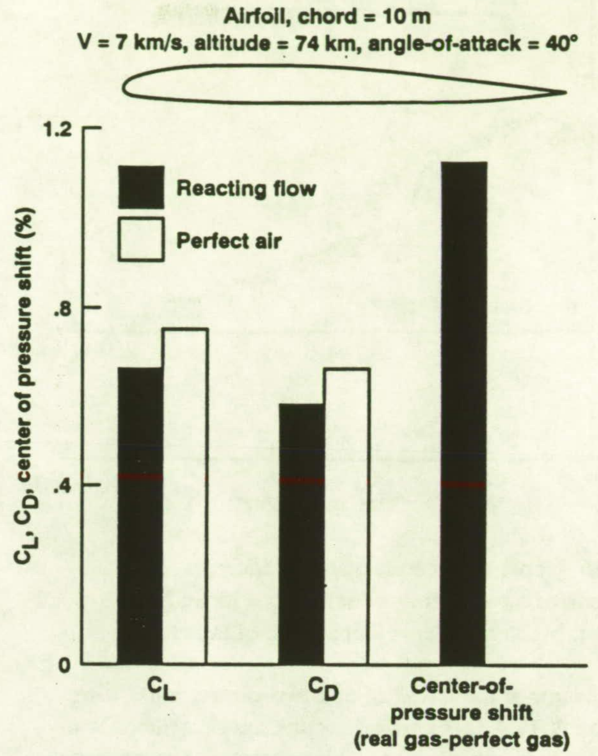

Fig. 15 Comparison of calculated real gas and perfect air airfoil lift and drag coefficients and center of pressure shift.

complete hypersonic vehicles, including flows through scramjet engines with additional complexities of combustion.

Measurement Techniques

Numerous advances are being made both in measuring various flow quantities without interference by the sensors and in more closely simulating flight environments in ground-based facilities. One such advance reported in Ref. 25 is the development of a method for nonintrusively obtaining pressures everywhere on an aerodynamic surface at any given instant of time. In this method, the surface is coated with an oxygen permeable polymer containing a luminescent molecule and then illuminated with ultraviolet radiation. The luminescence intensity distribution, which is related to the pressure, is obtained using quantitative video techniques while the surface is subjected to a flow. These results are then converted to a surface pressure map with the aid of computer processing. An example of early results taken from Ref. 25 is given in Fig. 16. Upper surface pressure

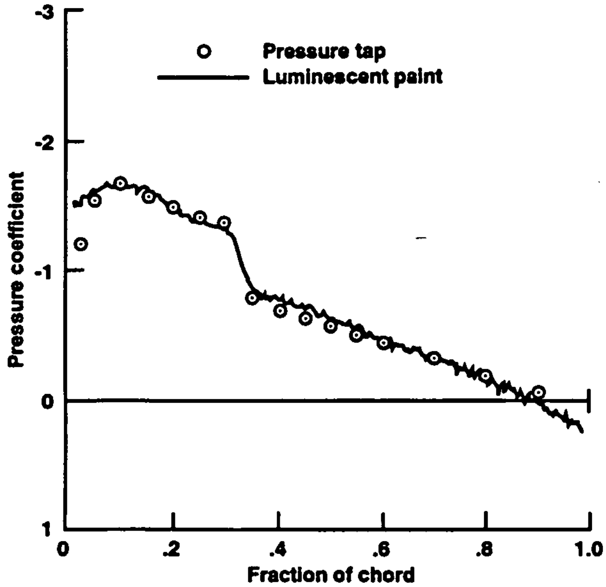

Fig. 16 Upper surface pressure coefficients at the midspan of a two-dimensional wing with an NACA-0012 section. Mach number = 0.66; angle of attack = 0.

coefficients at the midspan of a two-dimensional wing with an NACA-0012 airfoil section are presented for a flow Mach number of 0.66. Also shown for comparison are midspan chordwise pressures measured with conventional pressure taps. Excellent agreement between the two types of measurements is noted.

Reaction of the paint to pressure changes is reversible and rapid. This means that the same coating can be used over and over again, and likely can be used for pressure measurements in unsteady flow situations.

More recently, this method has been applied in wind tunnel tests of an oblique wing at supersonic speeds, and results are presented in Ref. 26. In addition, an initial study of the use of luminescent pressure sensitive paint in the flight environment using an F-104 airplane has been conducted and will be reported. Promising flight-test results were obtained along with information needed to improve application of the method in flight. Also under study is an extension of the method to simultaneously measure both temperature and pressure. Within the next few years, applied aerodynamicists should have a new tool that will provide pressures and temperatures everywhere on a test model, for both steady and unsteady flow conditions, all without installation of sensors.

Also under development are various methods for nonintrusively determining off-surface field measurements of temperature, density and pressure. One such method, described in Ref. 27, is a real-time interferometry system capable of providing densities and pressures in both steady and unsteady flows. Pressure distributions near the leading edge of an oscillating airfoil in compressible flow that were obtained using this method are presented in Ref. 28. Data such as these, together with velocity components measured with laser velocimetry, will be invaluable for improving understanding of aerodynamic flows and for validating computational methods.

Important advances also are being made in providing wind tunnel test environments more representative of free-air flight. These advances will permit studies of boundary layer transition and methods for its control in ground-based test facilities. One approach to obtaining low disturbance "quiet" flow in a small supersonic wind tunnel is reported in Ref. 29. This, and other approaches soon will be ready for use in large production-type facilities.

Numerical Optimization

The shape of an airplane is influenced by many factors other than aerodynamics. Among these are requirements imposed by desired dimensions of the payload compartment(s), mission range which influences fuel tank volume, dimensions of available engines, environmental considerations (sonic boom), and observability (military). Finding the optimum aerodynamic shape that satisfies constraints imposed by requirements such as these is a formidable task. It usually involves sorting through many possible configurations, suggested either by theoretical analysis or by experimentation, until the one having the "best" performance is obtained.

Availability of efficient numerical methods for calculating aerodynamic performance made it feasible to couple numerical optimizers to aerodynamic analysis codes to find an optimum shape based on various imposed constraints. Because of computer limitations, most applications of numerical optimization have been limited either to two-dimensional airfoils or to use of the linearized flow equations. Computers are now powerful enough, and analysis codes based on the nonlinear flow equations are now fast enough, to apply numerical optimization to realistic problems.

An example of the numerical optimization of a high-speed civil transport wing by using the Euler equations is presented in Ref. 30. The objectives were to start with a given wing planform and volume and find the airfoil shapes along the span that would provide maximum lift-to-drag ratio at a Mach number of 2.1, while keeping the wing leading edge radii and volume constant. Results for both baseline and optimized wings are shown in Fig. 17. Use of the optimizer improved lift-to-drag ratio at the design Mach number by 5.3%. It is interesting to note that lift-to-drag ratio at an off-design Mach number of 0.8 is about 20% higher than for the baseline wing. Obtaining these results required about 5-1/2 hr (340 min) of CPU time on a single Cray-YMP processor. This computing time should be reduced to less than 2 hr by next-generation supercomputers just coming to the marketplace. Before the end of this decade, applied aerodynamicists should be able to optimize an entire airplane shape by using Reynolds-averaged Navier-Stokes equations together with an optimizer.

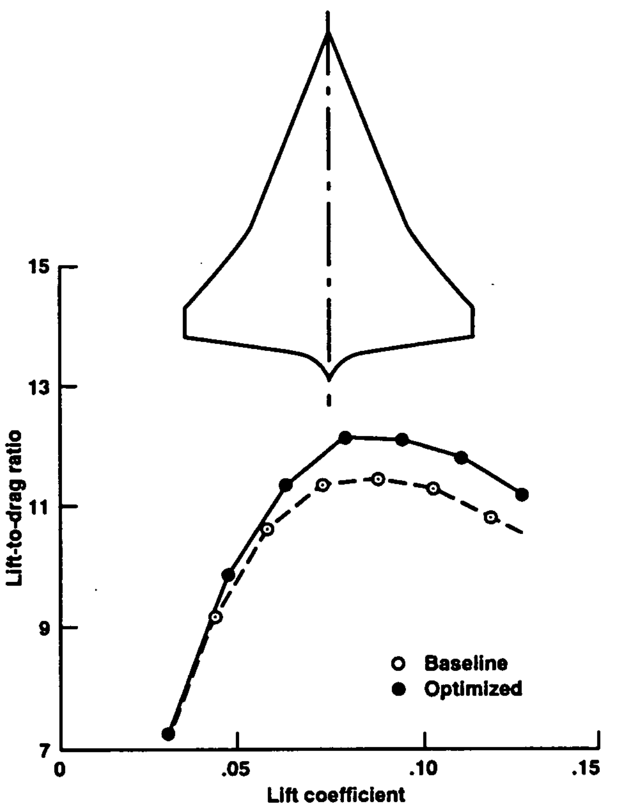

Fig. 17. Comparison of lift-to-drag ratios for baseline and optimized wings. Mach number = 2.1.

Multidisciplinary Analysis

Initiation of the High Performance Computing and Communication Program (HPCCP) has stimulated additional interest in developing computational tools capable of treating strongly coupled multidisciplinary phenomena, such as aerodynamics, structures, propulsion systems, and active controls. This interest was stimulated, in part, by a goal of the HPCCP to advance scientific computational capabilities by a factor of 1000 before the end of the decade. Without increases in available computer speed of this order, the ability to perform multidisciplinary analyses would remain limited. Additional background and discussion of goals of the HPCCP is presented in Ref. 31.

Aeroelasticity is an example of multidisciplinary phenomena that has been treated computationally for many years. This was made possible with already available computers by using forms of the governing equations that approximate underlying physics. With today's computers, it is practical in a research environment to couple the Reynolds-averaged Navier-Stokes equations with any one of a number of methods for approximating aeroelastic behavior of an aircraft structure. With future computers, one can envision coupling a NASTRAN code to a fluid dynamics code to provide even more precise results.

Another example of multidisciplinary analysis is the calculation of real gas phenomena including reacting flow chemistry associated with very high speed flight, hot exhaust flows interacting with aerodynamic surfaces, and combustion in the presence of flow through an engine. Still another is prediction of electromagnetic signatures where interactions are modeled of incident radiation with materials and irregular surface shapes.

These initial attempts to solve various multidisciplinary problems are pioneering methodology that eventually will be used to couple all disciplines important to aircraft design such as aerodynamics, structures, propulsion, and active controls. It will even be possible to include the discipline of electromagnetics when required.

Currently available computer power limits the number of disciplines that can be treated simultaneously, even when approximate forms of the governing equations are used. However, as computer power increases, more disciplines and less restrictive forms of governing equations can be introduced. Eventually, multidisciplinary design codes will be available that will provide solutions to problems with the use of reasonable amounts of computer time. Then, the time required to develop a new aircraft will be greatly reduced and improvements in the various measures of aircraft performance will be greatly increased.

Concluding Remarks

Aerospace is important to the country's economic competitiveness and military superiority. Both continued erosion of the U.S. world market share for commercial aircraft while the demand worldwide for aircraft is growing, and the concurrent reduction in expenditures for military aircraft, give applied aerodynamicists an unprecedented challenge to provide technology to offset these trends. A number of emerging research results have been discussed that will assist applied aerodynamicists in meeting this challenge in the relatively near term. However, substantial investments must continue to be made in basic and applied research efforts, focusing on increasing understanding of fluid dynamic phenomena, identifying new aerodynamic concepts, and providing validated technology for new aircraft, in order to continue to meet the challenge in the more distant future.

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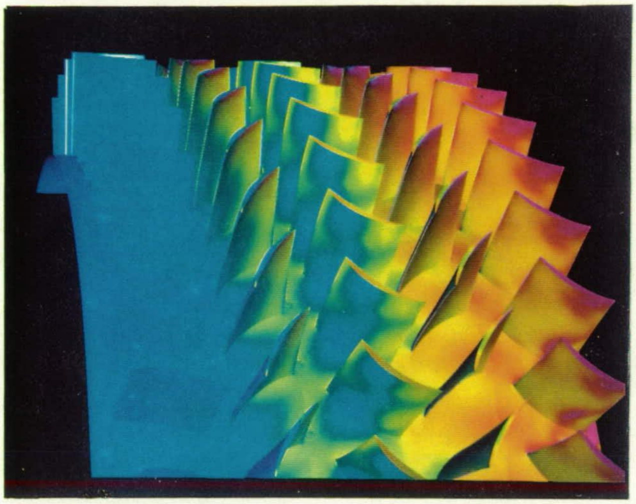

Fig. 5 Time-averaged surface pressure coefficients in the second stage of a 2-1/2-stage compressor.

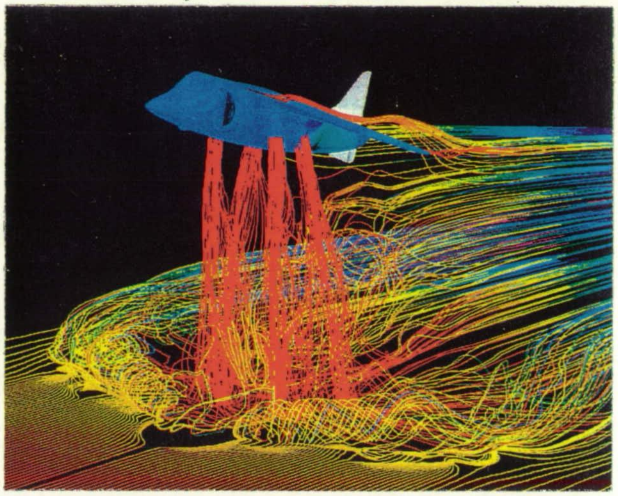

Fig. 10 Calculated flow about a Harrier aircraft 30 feet above the ground. Mach number = 0.04; angle of attack = 8°.

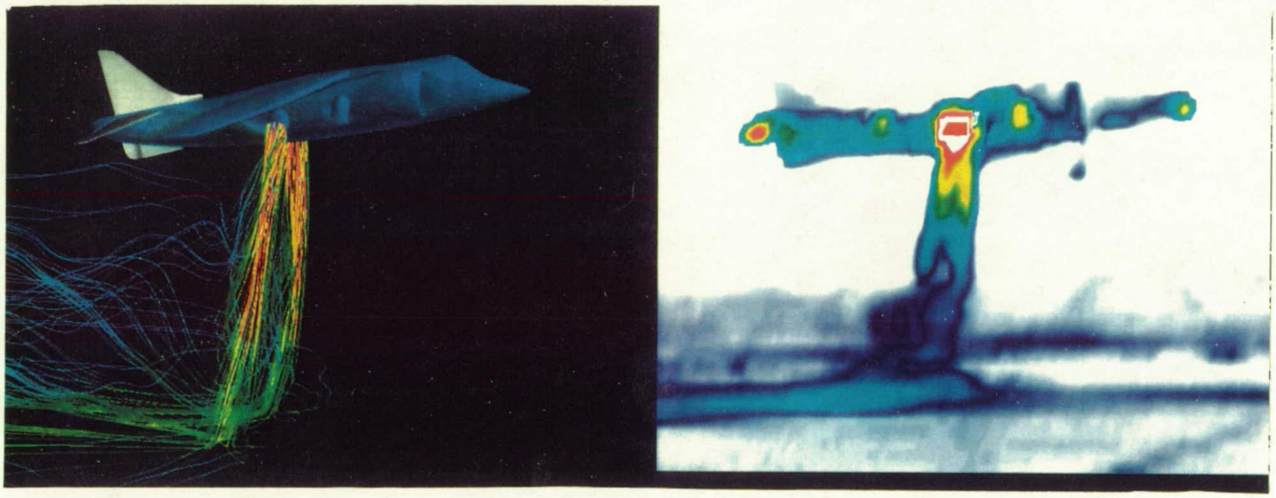

Fig. 11 Flow about a Harrier aircraft. (a) Computed, (b) Infrared measurements.

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13. ABSTRACT *(Maximum 200 words)*

Aerospace is the leading positive contributor to this country's balance of trade, derived largely from the sale of U.S. commercial aircraft around the world. This powerfully favorable economic situation is being threatened in two ways. (1) The U.S. portion of the commercial transport market is decreasing, even though the worldwide market is projected to increase substantially. (2) Expenditures are decreasing for military aircraft, which often serve as proving grounds for advanced aircraft technology. To retain a major share of the world market for commercial aircraft and continue to provide military aircraft with unsurpassed performance, the U.S. aerospace industry faces many technological challenges.

The field of applied aerodynamics is necessarily a major contributor to efforts aimed at meeting these technological challenges. A number of emerging research results that will provide new opportunities for applied aerodynamicists are discussed in this paper. Some of these have great potential for maintaining the high value of contributions from applied aerodynamics in the relatively near future. Over time, however, the value of these contributions will diminish greatly unless substantial investments continue to be made in basic and applied research efforts. The focus: to increase understanding of fluid dynamic phenomena, identify new aerodynamic concepts, and provide validated advanced technology for future aircraft.

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