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COMPUTATIONAL AERODYNAMICS AND DESIGN

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INTRODUCTION

In the last decade, advances in computer technology and data communications began to drastically change the way we live and the way we work. We bank, shop, make airline reservations, and pay our bills by using computers. Now, a new generation of children is growing up with computers in their homes and in their classrooms. This computer revolution has also had a major effect on the production of new aircraft. With the major investment of the aircraft industry in computer-aided design and computer-aided manufacturing (CAD/CAM), much of the development process from design through manufacturing is computer controlled. Furthermore, great progress is being made in computerizing the aeronautical disciplines that are the elements of design, such as aerodynamics, structures, guidance and control, and propulsion.

Nowhere has this progress been more exciting than in aerodynamics. The availability of modern supercomputers and the ingenuity of computational aerodynamics researchers have resulted in new methods for solving historically intractable nonlinear flow-field problems. Advances in data communications have facilitated remote access to these large computing engines, and advances in computer technology incorporated in mini- and midicomputers now provide sophisticated interactive graphics and data manipulation capability. All of these advances have profoundly affected the aerodynamic design process.

Here we assess the changing role of computational aerodynamics in design and consider the prospects for continued advancement.

THE TOOLS OF THE DESIGNER — THEORY AND EXPERIMENT

From the beginning, aerodynamicists have sought to use a proper combination of theory and experiment to achieve design objectives in a timely and cost-effective manner. The development of theoretical and experimental techniques has been motivated by a desire to assist the aerodynamicist in better understanding the influence of design variables on aerodynamic performance. In the early days of aviation, the Wright brothers built a small wind tunnel and even used some theory to enhance their understanding of aerodynamics (fig. 1).

In the decades since, the quality of wind-tunnel test techniques has continued to improve. Today these techniques are advancing at an evolutionary rate. Theoretical techniques also advanced, but this advancement was impeded by the nonlinearity of

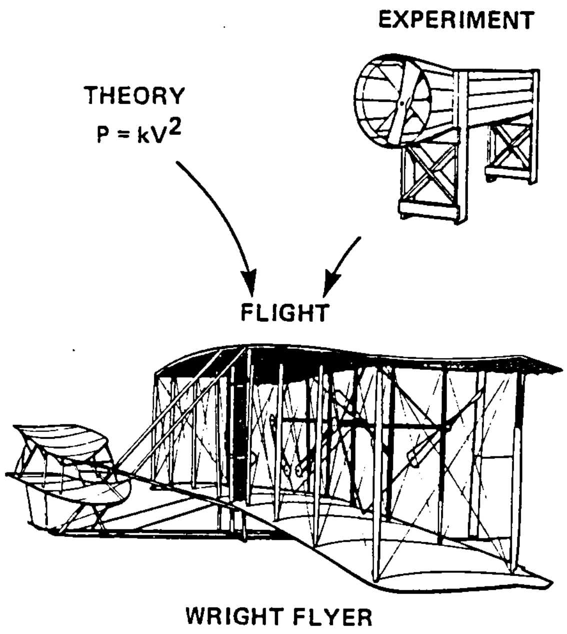


Fig. 1. In the beginning there was a blend of theory and experiment in aerodynamic design.

the simplified form of the partial differential equations governing fluid flows in certain flight regimes, such as the transonic Mach number range. In the late 1960s, computers sufficiently large to permit solution of these equations by finite-difference techniques became available. Computational aerodynamics has since advanced at a revolutionary rate.

In spite of the rapid advancement of computational methods, it is not expected that computational simulations will completely replace wind-tunnel testing in the foreseeable future. Their roles instead are complementary. Computations can provide some of the less intricate flow simulations required in design more quickly and at less cost than wind tunnels. They can also be used to make more effective use of wind tunnels by providing the means to (1) evaluate and improve new design concepts, such as swept forward wings or jet flaps for lift augmentation, before testing; (2) carefully discriminate among candidate configurations, eliminating all but the most promising before testing; (3) assist the aerodynamicist in instrumenting test models to improve resolution of the physical phenomena of interest; and (4) correct wind-tunnel data for scaling and interference errors. Computational simulations can also provide data for conditions that are outside the operating range of existing experimental facilities. An example would be a high-speed planetary probe entry condition, as in the Galileo Probe scheduled to enter the atmosphere of Jupiter in the late 1980s.

Inadequacies in testing (or analog simulations) are associated with limitations in operating range, such as Mach number, Reynolds number, gas composition, and enthalpy level, and the control of boundary conditions, such as flow nonuniformity, wall- and support-interference effects, and model fidelity. When these factors are properly controlled, the physical phenomena in the free-flight condition should be simulated correctly.

The inadequacies in computational (or digital) simulations are primarily associated with poor resolution of physical phenomena, and this is a direct result of insufficient computer power. If one accepts the unsteady compressible Navier-Stokes equations as an adequate system to describe aerodynamic flows, then physical phenomena of interest could be accurately simulated given sufficient computer power. However, current computer power is inadequate to permit numerical solution of these equations with suitable resolution of the wide range of length scales active in high-Reynolds-number turbulent flows. Hence, the aerodynamicist usually resorts to mathematical formulations that are approximations to the Navier-Stokes equations. These approximations introduce phenomenological errors, with the consequence that certain aspects of the flow-field physics are not properly represented. For any given mathematical formulation, the approximating procedures used to solve the governing equations and boundary conditions introduce numerical errors. Specifically, these errors are due to such factors as inadequate grid refinement or incomplete treatment of complex aerodynamic configurations. The consequences are again that physical phenomena are not properly represented. Both phenomenological errors and numerical errors can be reduced by increased computer power.

Because of the inherent differences in the nature of the two types of simulations, wind tunnels and computers are complementary: they have different inherent errors in simulating free-flight conditions. The principal point to be emphasized is that computational and wind-tunnel simulations are merely tools of the designer. Success in design depends very strongly on the judgment and expertise of the designer, his knowledge of aerodynamics, and his ability to use these design tools effectively.

THE ROLE OF COMPUTATIONAL AERODYNAMICS IN DESIGN

The Design Process

In recent years, aircraft design has been complicated substantially by the trade-offs that must be made to accommodate conflicting requirements. For commercial aircraft, these involve performance, cost, noise, and exhaust pollution, all of which are driven by economic and societal pressures. In the case of military aircraft, different mission profiles require trade-offs at multiple design points. For example, an aircraft may be required both to cruise and maneuver efficiently at transonic speeds and to accelerate rapidly to supersonic speeds and perform effectively in that regime. The optimum aerodynamic configurations that correspond to each of these design points are significantly different. This suggests aerodynamic designs with variable geometry, which further complicates the mechanical and structural design of the aircraft.

The process by which these requirements are converted into a production aircraft is illustrated schematically in figure 2 (M. Lores, Lockheed-Georgia, private communication, May 1982). The system requirements, as determined from customer requirements and mission analysis, feed into the conceptual design phase. From simple analyses and parametric variation studies, a conceptual baseline emerges. During the preliminary design phase, the concept is refined by means of more detailed analyses or exploratory tests or both. Design baselines are then allocated to each of the technical specialties. In the detailed design phase, detailed analysis or testing leads to final tests to verify the production baseline.

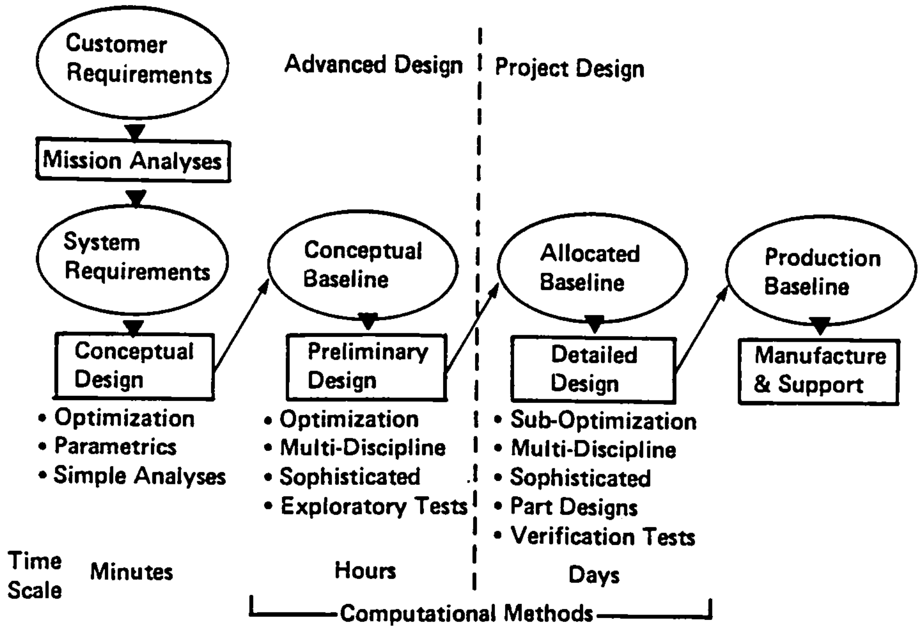


Fig. 2. The aircraft design process.

Levels of Use of Computational Aerodynamics in Design

Pierre Perrier (Dassault, private communication, Feb. 1982) defines four distinct levels at which computational aerodynamics is used in the design process. Level 0 involves no use whatsoever, with the designer relying on analysis, empiricisms, and successive wind-tunnel testing to refine the design. Level 1 involves extensive computation in the preliminary design (PD) phase followed by configuration refinement via wind-tunnel testing in the detailed design (DD) phase. Level 2 involves extensive reliance on computations in PD with a synergistic mixture of computations and wind-tunnel testing in DD. Final performance verification is obtained using wind-tunnel testing. At level 3, computational simulations are the principal design tool in both PD and DD, with some wind-tunnel verification provided at appropriate check-points in both PD and DD.

There is a variation among the broad range of designers of aerospace vehicles in the degree to which computations are relied on in the design process. It is fair to say that all major airframe manufacturers have progressed beyond level 0. That is, they all use computations at least in PD. The result has been a greater degree of management confidence in the designs emerging from the PD phase. Hence, larger performance gains are possible as a result of the consequently greater degree of design flexibility permitted. Furthermore, for the same budget, a greater degree of design refinement can be achieved before encountering the decision point that determines whether the project will continue.

Some manufacturers have not progressed beyond level 1 to the use of computations in DD, either because they do not consider aerodynamic refinements in their products to be highly important or because they lack confidence in their computational simulations. Generally, to reach level 2, a design group must have (1) a turnaround on their computations competitive with their wind-tunnel fabrication and test turnaround and (2) a high degree of confidence in their computational simulations, at least in the operating range near the design point. According to Raimo Hakkinen (McDonnell-Douglas, private communication, Jan. 1982), "The role of wind tunnel testing in transport wing design has evolved from that of almost complete dominance in the 1960s to the current one of verification testing after the final configuration candidates have been selected by computational methods. The total cost of the design process has been correspondingly reduced by an order of magnitude (in a recent project by a factor of 15), and a specific wing design can be evaluated in as little as 24 hours, instead of the several weeks normally required for fabrication and testing of a wind tunnel model." For fighter aircraft designs, which strain the limits of performance and require treatment of complex three-dimensional viscous flow phenomena, computations account for only about 20 to 30 percent of the aerodynamic design effort, according to Richard Bradley (General Dynamics, private communications, Jan. 1982). This percentage is expected to increase as computational treatment of these complex phenomena advances.

Level 3 use of computational aerodynamics is still very rare, although there are some outstanding examples, usually involving only minor to moderate changes to some base configuration that has been extensively tested. The Dassault Falcon 50 is one of these examples. In the case of this transatlantic business tri-jet, a new computationally optimized wing was introduced in fabrication and flight test with only one low-speed and two high-speed wind-tunnel test series (P. Perrier).

The potential payoffs from the extensive use of computational simulations at levels 2 and 3 are high, but there is a significant risk that must be addressed. Generally, testing occurs later in the design cycle in levels 2 and 3 than in levels 0 and 1. Before verification tests are performed, the aerodynamic design cannot be considered frozen, and hence the nonaerodynamics groups cannot freeze their designs. Should difficulties be uncovered late in the design cycle by verification tests, development cost, schedule, and performance can be significantly affected. On the other hand, computations can significantly shorten the time required for design; they also provide the designer a tool with which design deficiencies, once uncovered, can be quickly corrected.

A management technique that has worked effectively at Dassault and some companies in the United States is to pursue design refinements computationally as an off-line project activity. That is, computational simulations are not relied on in DD and hence cannot adversely influence the project critical path in terms of cost, schedule, and performance. These simulations are undertaken by a design team working off-line and seeking improvements that can be made available to the project in a timely fashion. Whether these improvements should be incorporated in the project design is a decision that must be made by the project manager. Frequently this type of off-line effort can reduce design time (and, hence, cost) and improve performance.

If the computational design team is not successful, they do not adversely affect the project cost, schedule, and performance beyond that which was anticipated in the original project plan.

Some Lessons from the Experience of the Last Decade

The current level of integration of computational simulations into the design process has resulted from the learning experience of more than a decade. This experience began with research in numerical solution techniques, followed by the development of computer codes based on the products of that research. Extensive evaluation and experience with these codes has resulted in their gradual acceptance by the designer and his management. And so the process continues, as improved solution techniques are devised.

Many lessons have been learned, including the following: (1) the proper role of computations can be easily misunderstood by the designer and his management; (2) calibration, interpretation, and verification are all essential elements in adapting computational analysis to design; (3) there are definable factors that determine the degree to which a given computational capability is useful; (4) new codes must be marketed carefully — acceptance will be gradual; and (5) aerodynamics is still an art — no entirely satisfactory procedure has yet been devised to assist the designer in defining aerodynamic shapes for specified performance objectives and design constraints. Each of these items is addressed in turn.

Proper role of computations — It is now generally accepted among aerospace designers and managers that computations should be used extensively in vehicle design. The question is no longer whether these methods should be used but how to get them to do more. This current attitude is a result of a lengthy educational process. According to M. George (Northrop, private communication, Feb. 1982), "In the beginning, the codes were expected to provide 'answers,' i.e., actual drag, lift and moment data. Today, with greater acceptance and more extensive use, the codes are used to provide information such as shock formations, for example, and other flow characteristics and phenomena which are the causes of aerodynamic performance. Such analysis was previously impossible without expensive, time-consuming tests. Today, the codes have become an integral part of the design process — that process in fact is dependent on the availability and use of computational methods."

Generally, computations are useful in providing the aerodynamicist with an understanding of the effects of configuration modifications on the features of the flow field. They are normally not reliable in predicting absolute performance values for a given configuration. Failure of the designer or his management to understand the proper use of computational aerodynamics can cause him to abandon its use and, hence, lose the advantages that derive from it.

Importance of calibration, interpretation, and verification — Extensive experience with computations in aerodynamic analysis and design indicates the importance of calibration, interpretation, and verification. The aerodynamicist, because he understands that there are numerical and phenomenological errors associated with computational simulations, must calibrate his computational tools before applying them. Normally, computed results are correlated with available wind-tunnel data for some representative baseline configuration to determine the extent to which the computations represent the essential flow-field physics. Discrepancies are reduced by appropriate "tuning" to empirically model those physical features of the flow that are not adequately treated by the particular computational approach in use.

For the case of an inviscid computational simulation, this could involve modeling the boundary layer, by assuming an appropriate displacement thickness, and the shock/boundary-layer and trailing-edge flow conditions. For the case of wing design using a code that is capable of solving only flow past a wing, some means must be used to model the effects of the fuselage and other aircraft components on the wing flow. Deficiencies in the computations, with appropriate modeling included, must be accounted for by skillful interpretation of computed results. Guidance for interpretation is provided by results of the calibration. Once properly calibrated, the computer code can be used by the designer to solve the aerodynamics problem of interest. In the case of a design problem, the computer code can be used to help define the aerodynamic shape that best meets performance objectives while satisfying design constraints. Because the computation normally is not reliable in establishing the absolute level of performance, experimental verification is required before the design can be accepted.

Usefulness of a given computational capability — For an aeronautical engineer to decide to invest his time to learn how to use a new computer code, there must be clearly evident gains in capability relative to previously existing codes or procedures. Capability is measured in terms of accuracy and reliability, run cost and turnaround time, ease of use, and versatility. A designer will use only those computational tools in which he has confidence. He builds this confidence through extensive experience in comparing computed results with validated data — the calibration process. This gives him a measure of accuracy and reliability, as well as run cost and turnaround time. For any given analysis then, he has the information required to determine which of the tools he has calibrated can provide acceptable accuracy at minimum cost in the time required.

In high-priority design activities, turnaround dominates cost considerations. In design studies constrained by tight computer budgets, the opposite may be true. However, in assessing cost and turnaround time, one must consider the time and cost of people, as well as the time and cost associated with computer facilities. Ease of use, or code "friendliness," is directly associated with these time and cost factors. Friendliness refers to such features as ease of manipulating data; the effort involved in the input of data (especially geometry data) and post-processing of flow-field data; the degree to which input/output is consistent with other codes used by the organization; code transportability and maintainability; and code structure and readability. Versatility refers to the scope of applications to which a code can be applied. It is certainly easier to justify the time investment required to learn the use of a new code if that code can be used in a wide range of applications that are of interest to the organization.

Marketing new codes — New methods and new codes, like any new product, must be marketed very carefully. Premature release can result in reputation assassination, virtually guaranteeing that the new technology will not be accepted by the user community. This discourages early release of new technology to potential users; the code developer seeks to wring all of the "bugs" out of a code before its release. Hence, detailed testing of the software is continued until the code is thoroughly certified, with the consequence that its release is delayed 1 to 2 years. An alternative approach is to risk early release of an incompletely tested code to a carefully selected group of users. These users are then scrupulously serviced by the code development team. For example, the team can keep a record of all cases run, of the input and output, and of other information necessary to determine the causes of failure in any given run. Deficiencies in the use of the code are quickly corrected. Records are kept to document deficiencies in the code itself, which can then be corrected with changes appropriately documented.

The advantage to the code development team is that the select group of users assists in debugging the code in practical applications. Furthermore, this initial group of trained users can then train additional users, relieving the code development team of that burden. The advantage to the users is early access to a new analysis/design capability. Moreover, these initially trained users are recognized as valuable assets within a company — their services are in demand by a number of project managers. Experience indicates that acceptance of any fundamentally new computational technology by the aerodynamicist and his management is a gradual process. It occurs in any company only after an extensive calibration phase during which the capabilities and proper use of the new technology are thoroughly evaluated.

Aerodynamics is still an art — The need to control the vast amounts of information involved in modern design has led to increased use of aircraft synthesis computer codes to combine all of the technical specialties so that an integrated design solution can be achieved quickly and efficiently. In such an environment, the design flexibility available to the aerodynamicist is limited, and the interfaces with the other aeronautical specialties are clearly defined. Within these defined limitations, the aerodynamicist must first formulate a definition of the design problem in terms of aerodynamic performance objectives and then decide on the specific approach to be used to solve the problem.

Two distinct problem solving approaches can be identified. The first, which we might call the conventional approach, begins with analysis and then leads to detailed wind-tunnel testing of a limited number of candidate configurations. From the resulting performance data, a configuration is selected as the solution to the problem, or new configurations are selected for further testing. In this approach, computational simulations may or may not be used in defining candidate configurations for wind-tunnel testing. The second approach is called direct design, or optimization. Here, the aerodynamicist formulates and solves a constrained optimization problem, defining a function to be minimized (e.g., the drag or some combination of performance parameters) for a set of decision variables that represent the configuration shape, subject to a set of imposed constraints. The constraints generally involve limitations on geometrical flexibility and acceptable levels of aerodynamic performance. Computational simulations are a fundamental part of the optimization approach; they are required to compute the objective function for various test design variables used in searching the design space.

Notice that in the conventional approach, the final selection is based on the testing of a limited number of candidate configurations, but over a broad range. Only a narrow design space can be searched, and it may not include the best feasible design. In the optimization approach, the focus is on producing a single configuration that represents the best trade-off of design objectives subject to the imposed constraints, and in principle an infinite number of candidates have been considered in choosing the optimum configuration. However, only a limited number of design points are considered. Consequently, performance difficulties may be encountered at other points in the operating range of the aircraft. The design techniques in current use are combinations and variations of the two approaches outlined above specifically tailored to solve a particular problem.

EXAMPLES OF COMPUTATIONAL AERODYNAMICS IN DESIGN

This first example illustrates how new computational technology is integrated into existing design procedures. The Highly Maneuverable Aircraft Technology (HiMAT) design (fig. 3) took place in the mid-1970s and was the first in which a nonlinear, three-dimensional, transonic finite-difference code was used in an aerodynamic design (ref. 1). The HiMAT project objective was to develop and evaluate high-maneuverability technologies and to synthesize those technologies in a remotely piloted research vehicle (RPRV). The specific aerodynamic objective was to improve fighter maneuver performance without compromising other mission requirements, such as cruise performance and supersonic acceleration capability. The tight budget, typical of this type of technology demonstration project, and the ambitious performance goal required heavy reliance on analysis and computations with a minimum of wind-tunnel testing.

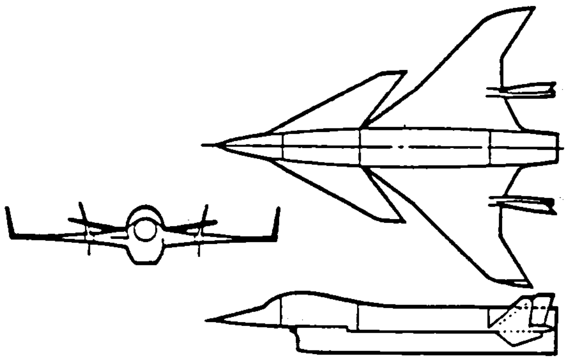


Fig. 3. HiMAT RPRV three-view.

The design-team strategy was to optimize the basic design for high maneuverability and then to determine an acceptable cruise configuration that could be achieved using a variable camber system and preprogrammed twist increment due to structural bending. The preliminary design and initial stages of the detailed design would be conducted using linear theory, a linear inviscid approximation to the Navier-Stokes equations. This computational approach is cost-effective and, in its present mature stage of development, is capable of treating complex aerodynamic configurations. However, it does not properly account for shock waves or other nonlinear phenomena encountered in the transonic regime. Refinement of the configuration to meet transonic performance requirements would subsequently be accomplished using the Bailey-Ballhaus (B^2) nonlinear transonic code (ref. 2), a less approximate formulation for transonic flows than linear theory. Wind-tunnel tests would be conducted at appropriate stages of the design as needed.

The baseline wing-canard design was achieved after several linear theory design iterations. The design exhibited good subsonic drag characteristics but, as expected, was deficient at the transonic design point ($M = 0.9$). Wind-tunnel oil-flow visualization indicated shock-induced separation on the outboard wing and canard and a strong unswept shock wave near the trailing edge of the inboard wing. These flow features were primarily responsible for the excess drag at $M_\infty = 0.9$ shown in figure 4 for the linear theory design.

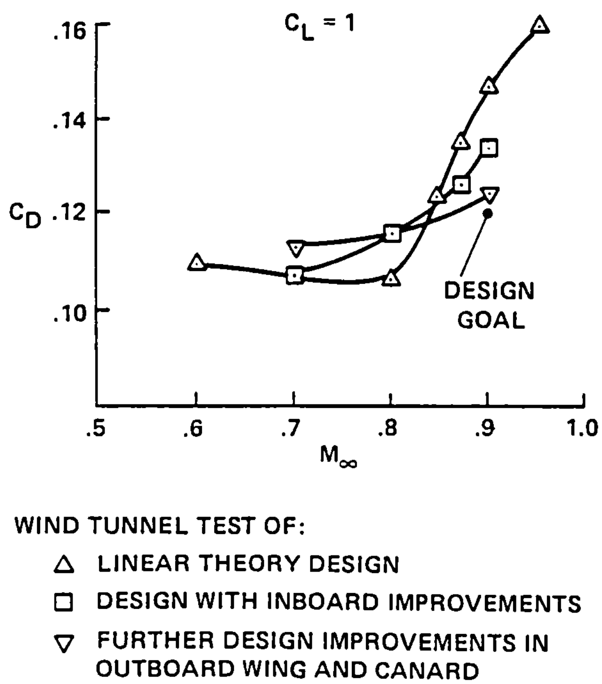
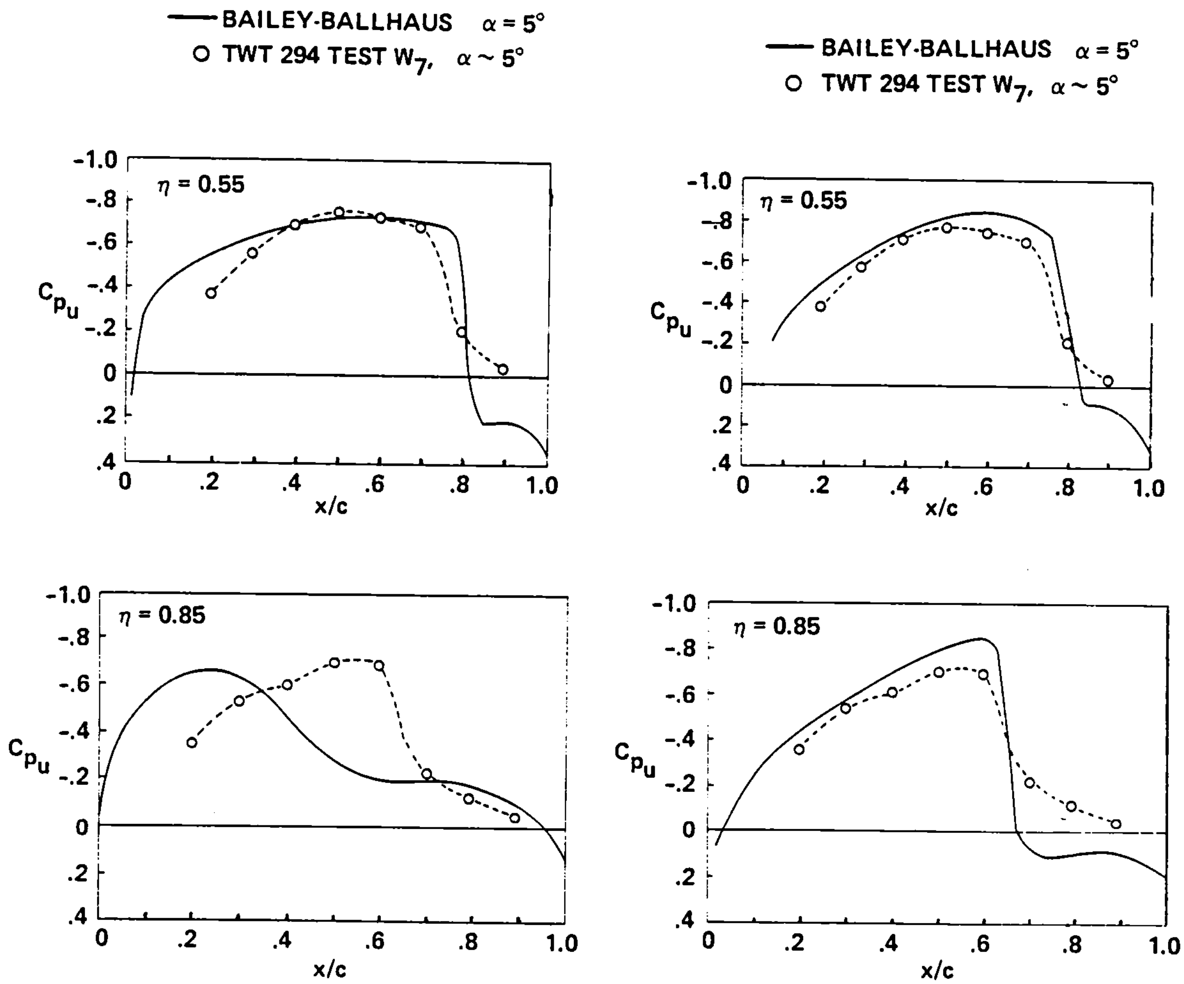


Fig. 4. Reduction of HiMAT maneuver configuration drag rise.

To more thoroughly understand the configuration deficiencies and to provide data to calibrate the B^2 code, a wind-tunnel test was conducted in which upper-surface pressures were measured. Comparisons of these measurements and B^2-computed pressures for two span stations are shown in figure 5a. The B^2 code accuracy was found to be acceptable in the inboard 70 percent of the semispan, where the shock wave was not highly swept. However, it failed to capture the highly swept outboard shock. This deficiency had been anticipated by the code authors (ref. 3) and was eventually corrected (ref. 4), as indicated in figure 5b, but not in time to influence the HiMAT design. Consequently, the B^2 code was applied to improve the design only for the inboard 70 percent semispan region. The B^2 code was also incapable of including the canard in the flow-field computation. During the calibration phase, it was determined that the effect of the canard on the wing flow could be modeled by superimposing an appropriate amount of wing twist on the geometrical twist of the wing in applying the wing boundary condition.

With these improvements, the code could be used effectively to guide the designer in modifying the wing shape to improve the wing flow and thereby reduce the transonic drag. The airfoil sections and wing planform were modified in a trial-and-error manner to minimize the computed strength and extent of the shock without sacrificing lift. This was continued until suitable pressure distributions were obtained. Verification wind-tunnel tests of the resulting configuration indicated that the computationally derived modifications were successful in weakening or eliminating shock waves over much of the inboard 70 percent of the span. This resulted in a major



(a) Original B^2 code. (b) Improved B^2 code.

Fig. 5. HiMAT wing surface pressure comparisons at two span stations.

reduction in drag. In the outboard region, where the flow was nearly two-dimensional in a plane normal to the sweep direction, a two-dimensional nonlinear transonic code and sweep theory were used to improve the configuration. This further reduced the drag so that the final configuration, when tested, indicated a substantial improvement over the linear-theory design (fig. 4).

The HiMAT design illustrates how new computational technology is accepted by the designer. The motivating force behind the use of the B^2 code was the need to solve a particular transonic design problem, in the midst of a design effort, that could not have been solved within schedule and budget constraints by using existing procedures. The Rockwell research staff acquired this code before it had been thoroughly tested and certified, extended it in consultation with the code developers to treat the winglets at the wingtips, calibrated it to understand its deficiencies, and modeled the effect of the canard on the wing by introducing appropriate twist in the wing boundary condition. They applied the code only where calibration studies indicated it could be used reliably (the inboard 70-percent semispan). They used it effectively to find configuration modifications that would improve features of the flow that the code could provide reliably, that is, pressure distributions, and subsequently conducted wind-tunnel tests to verify the absolute level of drag performance. Finally, they interacted with the code developers, providing valuable feedback that was used to improve the code for future design efforts.

The HiMAT design approach involved a combination of computations and wind-tunnel tests. Budget limitations precluded the extensive testing normally associated with the conventional design approach defined in the preceding section. Although some optimization was used to obtain the linear theory design, the primitive stage of development and excessive run time of the B^2 code precluded its use in an optimization mode for refinement of the transonic design. Hence, a trial-and-error approach was used. The following example, design of a helicopter rotor airfoil section, seeks a more direct approach toward configuration refinement by use of optimization.

A schematic flowchart of a typical optimization process is depicted in figure 6. The hypothetical design problem shown is drag minimization with three design variables (h_1, h_2, and h_3). Here the objective is to minimize the airfoil drag by varying the design variables that describe the shape of the airfoil. The optimization process begins with an initial specified airfoil shape. Constraints can be imposed on the geometry of the airfoil (e.g., minimum thickness), on aerodynamic performance (e.g., minimum lift), and on flow-field characteristics (e.g., maximum shock strength). The computer is then free to minimize the objective function, subject to the imposed constraints, by varying the design variables.

The first step in the design process is calculation of the aerodynamic coefficients of the initial airfoil. These coefficients are stored as baseline values for future use in the gradient calculations. The optimization program then perturbs each of the design variables, one by one, returning to the aerodynamics program for evaluation of the aerodynamic coefficients and the partial derivative of drag with respect

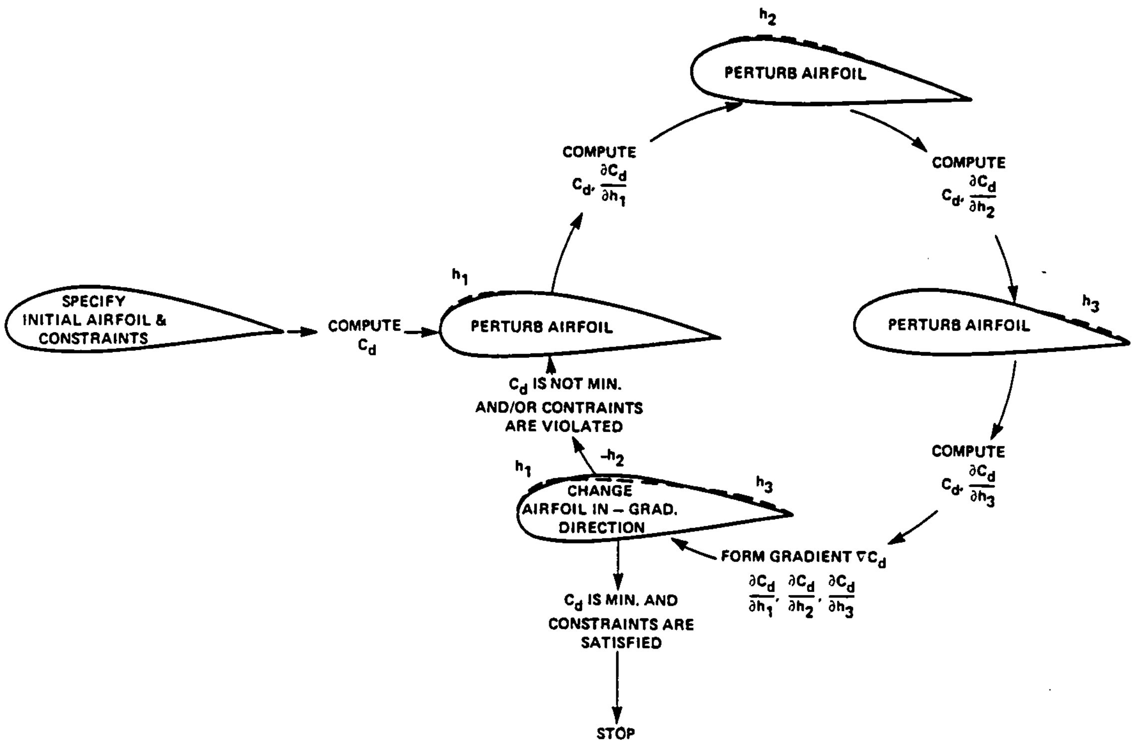


Fig. 6. Drag minimization by numerical optimization, 3 design variables.

to each design variable after each perturbation. The partial derivatives form the gradient of drag (∇C_D). The direction in which (h_1, h_2, and h_3) are displaced to reduce the drag coefficient is $-\nabla C_D$ (the steepest descent direction). The optimization program increments the design variables one to four times in the direction indicated by $-\nabla C_D$. The process continues until the drag begins to increase as a result of nonlinearity in the design space or until a constraint (such as airfoil thickness) is encountered.

The specific choices of objective function, constraints, initial airfoil shape, and design variables describing the airfoil shape relative to the baseline airfoil are all selected by the aerodynamicist. Experience indicates very clearly that the success of the design optimization depends strongly on the judgment of the designer in making these choices.

Design of helicopter rotor airfoil sections requires simultaneous consideration of several design requirements. Example requirements are high maximum-lift coefficients and good stall characteristics for Mach numbers of 0.3 to 0.5, a high lift/drag ratio at $M = 0.6$ and $C_\ell \sim 0.6$, and a drag divergence Mach number of at least 0.8, no drag creep, and low pitching moments over most of the Mach number range. To achieve all of these conditions, the optimization code must monitor and constrain certain aerodynamic parameters at five or six different combinations of Mach number and angle of attack.

Such a design was attempted by Hicks and McCroskey (ref. 5) in which, to reduce computing time and cost, only some of these conditions were considered. The shock drag coefficient at $M = 0.82$ and $\alpha = 0°$ was chosen as the objective to be minimized. Constraints were imposed on the shock drag coefficients ($C_d \leq 0.001$) at $M = 0.4$, $\alpha = 12°$, and at $M = 0.5$, $\alpha = 10°$ to delay retreating-blade shock stall. The standard Jameson FLO-6 transonic full-potential airfoil analysis code (ref. 6), linked with a standard constrained function minimization code, was used in the design. These codes had been extensively calibrated in other airfoil designs. The initial airfoil section from which the design optimization was initiated was the Wortman profile, designed for helicopter applications and known for its desirable rotor characteristics.

The resulting airfoil section, called the A-1 section, was tested in the 2- by 2-foot wind tunnel at Ames. A comparison of the A-1's improved performance relative to the baseline section (Wortman FX69-H-098) and a classical rotor section, the NACA 0012, is shown in figure 7.

Computational simulations have been used effectively in a number of recent major aircraft development programs. The Airbus A-310 and Boeing 757 are examples in which computational simulations have played a significant role in achieving new designs that are substantially more fuel efficient than their predecessors. As these simulations become more useful, aircraft companies are becoming less willing to provide information concerning their application. Consequently, there are many interesting examples that, unfortunately, cannot be described here.

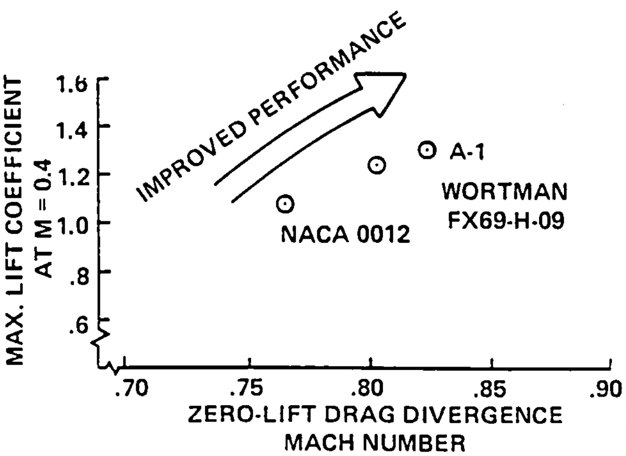


Fig. 7. Verified performance improvement from helicopter airfoil optimization.

PROSPECTS FOR THE FUTURE

Although computational simulations have become considerably more useful in design during the last few years, there is considerable room for improvement. Increasing design cost and complexity, as well as increasing performance objectives of new aircraft, drive the search for more accurate and more cost-effective computational capability. The complexities of the obstacles involved ensure that this search will continue for many years. The major areas of consideration are (1) the availability of advanced computers, (2) advancements in numerical solution techniques, (3) improvements in turbulence models, (4) treatment of complex geometries, and (5) improved computational design procedures.

Advanced Computers

The prospects are good that significant increases in scientific computing capability will become available in this decade. From a technical standpoint, anticipated advances in component technology point to improvements in speed of at least an order of magnitude. Moreover, architectural advances permitting multiple processors to efficiently address a single problem with a common data base offer opportunities for further orders-of-magnitude improvements in speed. There will also be advances in memory size and in data transfer rates to support such improvements in speed. Significant attention will be directed toward developing software to assist the user in taking full advantage of these architectural advances.

The slowdown in advances during the last decade, prompted by marketing considerations rather than technical ones, appears to be reversing. The anticipation of increases in the size of the market for leading-edge scientific computers has led to increased competition within the industry. Moreover, recent government policies reflect a growing realization that the large-scale scientific computer is a fundamental tool affecting the rate of progress in a wide range of technical disciplines (this is especially true in Japan, where advances in scientific computing have become a national objective). Furthermore, large machines are becoming accessible to a broader range of the user community. Until recently, leading-edge scientific computers in the United States have been installed primarily in the national research laboratories, with the airframe manufacturers and universities enjoying only limited access to them. Now, several of these large computing engines have been installed at universities and at least one aircraft company.

Extensive experience with supercomputing, primarily in the national research laboratories, has provided some observations that illustrate both its power and its limitations. The first observation is that <u>it takes a larger computer to develop a new computational capability in a research mode than it does to implement that capability in applications</u>. Once a previously intractable problem is solved, then significant improvements in accuracy and efficiency are subsequently achieved by a combination of analysis and computational experiments. This experimentation requires rapid turnaround which, for problems that strain the limits of existing capability, can only be achieved with the largest and fastest existing computing engines. The algorithm refinements that result frequently reduce computer run-time to the point where the new capability can be implemented on smaller systems. For example, much of the development work for inviscid transonic aerodynamic methods and codes was done on CDC-7600-class machines. Computer run-times have been reduced by more than an order of magnitude. Now, these codes can be run in minutes on slower, less expensive machines like the VAX 11/780.

The second observation is that people are becoming more expensive than computer hardware. In human-computer interactions, maximum effective use of people is becoming at least as important a measure of efficiency as maximum use of computer cycles. Human effort to construct data bases for processing must be considered along with computer run-time in assessing the total cost of a computational simulation.

The third observation is that large upgrades in computer power are required to produce moderate improvements in simulation capability. Doubling the number of grid points in each direction to improve resolution results in a factor-of-8 increase in the number of total grid points in the field. This usually results in more than a factor-of-8 increase in computer run-time to get only twice the resolution. Hence, minor improvements in computer power usually result in insignificant improvements in accuracy.

Advances in Numerical Solution Techniques

Advances in numerical solution techniques offer prospects for increasing computational simulation capability at a rate comparable to that resulting from increasing computer capability. An excellent illustration of this was provided recently by Holst in a computation of inviscid full-potential transonic flow about the ONERA M-6 wing, $M_\infty = 0.84$, $\alpha = 3°$. This case has been used by a number of researchers to test new methods. The base code used was FLO-28 (ref. 7), which solves the full-potential equation in conservation-law form, using successive-line overrelaxation, a standard solution technique. The computation took 742 sec on the CDC-7600 computer to reach 98 percent convergence on lift coefficient. Holst, using an improved implicit factorization algorithm to solve the same governing equation, achieved the same degree of convergence in 64 sec — an improvement of better than an order of magnitude (ref. 8). By running the code on the faster Cray 1S machine, after first vectorizing the coding to take advantage of the Cray's special architecture, a solution was obtained in 4.8 sec — a further improvement of better than an order of magnitude (T. Holst, NASA Ames, private communication, March 1982). With a run-time less than 5 sec, achieved through advances in both algorithm efficiency and computer power, over 150 wing-flow simulations can be obtained in the same time, and for very nearly the same cost, as for a single flow solution using FLO-28 on the CDC-7600. Furthermore, an aerodynamic analysis code with a 5-sec run-time can be used effectively for design in the optimization mode.

Such dramatic advances in solution techniques for the full-potential formulation provide encouragement for similar advances in techniques for solving the less-approximate Euler and Reynolds-averaged-Navier-Stokes (RANS) formulations. Relative to the full-potential formulation, the Euler formulation is a more accurate simulation of flow-field physics, in that it provides for the treatment of rotational flows, including vortices and strong shock-wave effects. The RANS formulation, combined with a suitable turbulence model, further provides for the treatment of viscous effects, including flow separation.

This capability is fundamentally important for simulating aerodynamic flows near performance boundaries. However, these formulations require considerably more storage and computational work to obtain a solution than the full-potential formulation, and current computer power and solution techniques are inadequate for these formulations to be widely used in design. Nevertheless, major reductions in computer run-time are anticipated during the 1980s by overcoming unnecessarily severe constraints on integration time-steps (frequently a result of stability rather than accuracy considerations).

Further reductions in run-time, and significant reductions in storage, will be achieved by the development of solution-adaptive grid techniques. That is, the distribution of grid points will be determined dynamically, as the solution evolves. Grid-point distribution then will be solution-dependent, with grid-point locations chosen to maximize accuracy for a specified number of points.

Turbulence Models

The dynamics of turbulence in the wide range of scales encountered in practical aerodynamics problems cannot be simulated using either present computer power or that anticipated for many years to come. Hence, the flow variables in the Navier-Stokes equations are averaged over a time period that is long compared with the time scales associated with predominant features of the turbulence (Reynolds-averaged-Navier-Stokes formulation). The number of unknowns then exceeds the number of equations. The process of expressing the unknowns as transport equations or functions in terms of known quantities is called "turbulence modeling." No entirely suitable model for all flow types of engineering interest has yet been discovered.

The current predominant thinking among researchers in the field is that no such universal turbulence model exists. Hence, attention is now focused on developing menus of turbulence models. The process consists of a synergistic use of computation and experiment to develop and test models for various types of flows that are considered building blocks to more complete aerodynamic configurations, such as attached flows with and without curvature and imposed pressure gradients, simple separated and reattached flows, flows with shock waves, and airfoil trailing-edge flows. The state of the art is such that simple attached flows can normally be adequately treated. Three-dimensional cases with large amounts of skewing of flow direction in the boundary layer still present a considerable challenge. Complex flows with massive separation can often be properly simulated qualitatively but not quantitatively. For a more thorough discussion, see reference 9.

Complex Geometries

One of the initial steps in a flow-field computation is the specification of boundary conditions. For aerodynamic flows, digital data describing the configuration shape of interest must be provided. A finite-difference grid system is then generated which encompasses the flow-field domain and serves as the basis for finite-difference approximations to the terms in the governing flow-field partial differential equations. The principal difficulty involved in the analysis of complex aerodynamic configurations is the generation of a suitable grid system.

A number of factors must be considered in assessing the suitability of a grid system. The object is to achieve required accuracy with the minimum number of grid points and with the least effect on the flow-solution algorithm owing to singularities or other special considerations. An example grid for an aircraft nacelle flow field is shown in figure 8 (from ref. 10). The grid is adapted to the surface of the nacelle and the grid points are clustered in regions, such as the leading edge, where large flow gradients in the solution are anticipated. This grid was generated for only a single component — the nacelle.

Major difficulties are encountered in treating multiple component configurations, for which component-adapted grids must be interfaced. These interfaces introduce difficulties in the solution process in that they complicate coding and adversely affect run-time and numerical accuracy. Extensive effort, especially in the aircraft companies, is contributing to a very gradual expansion in the complexity of configurations that can be adequately analyzed. For the time being, however, linear theory will continue to be used for analyzing aerodynamic configurations in detail. Linear theory, as described in the HiMAT example, requires generation of a grid system only on the boundary surface, not for the entire flow field. Because the resulting grid-generation problem is so much simpler, this simple formulation can be used to analyze practical aerodynamic configurations to a much greater degree of detail than can be achieved with the more physically complete nonlinear formulations (full-potential, Euler, and Reynolds-Averaged-Navier-Stokes).

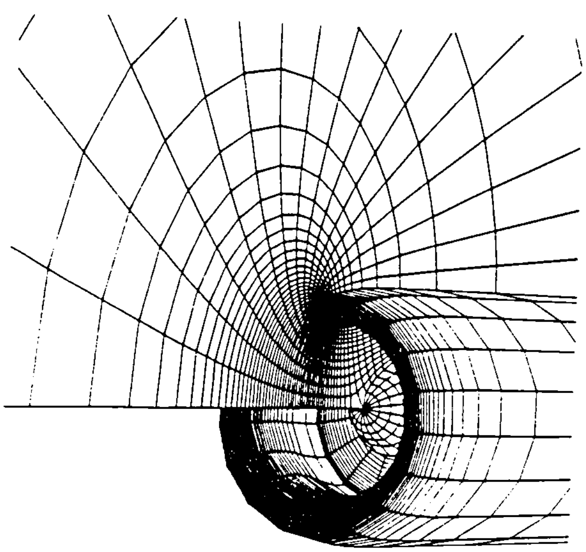


Fig. 8. Perspective view of three-dimensional coordinate system for a nacelle.

Computational Design Procedures

One of the principal advantages of computational simulations relative to testing is the opportunity they offer to compute a vehicle geometry that yields some desirable aerodynamic characteristic.

Optimization, as illustrated by the helicopter airfoil design described in the preceding section, is a promising approach toward taking advantage of this opportunity, providing the designer can supply the judgment required to use it effectively.

To begin with, great care must be taken in selecting some controllable parameter or function of several parameters as the objective to be minimized. Experience indicates that since total drag is usually not predicted reliably, the emphasis must be on obtaining configuration modifications that eliminate or at least weaken shock waves, eliminate embedded supersonic flow on fuselage cabin regions, minimize adverse pressure gradients, etc. Success also depends strongly on the number of design variables that define the configuration shape and the extent to which these design variables permit flexibility in the design (i.e., can a near-optimum shape be described from some suitably chosen values of design variables selected). Finally, since many flow-field computations may be required to achieve an optimum design, only those methods with suitably short run-times for a single flow-field computation can be used in an optimization mode.

Optimization can be used to improve the effectiveness of other design techniques. For example, it can be combined with the inverse approach to permit specification of performance and configuration constraints. In the inverse approach, a configuration shape corresponding to a pressure distribution selected by the aerodynamicist is computed; the pressure distribution selected is one that his experience indicates will provide the desired performance. The combined optimization-inverse approach would seek that configuration that best fits the specified pressure distribution while satisfying the imposed constraints.

Clearly, much remains to be done to provide a more direct and systematic approach to design than trial and error. The usefulness of optimization and other approaches will depend on the degree to which computer run-time for complete three-dimensional flow simulations can be reduced by a combination of more powerful computers and improved solution algorithms. It will also depend on how accurately flow-field physics and geometrical detail can be simulated to relate configuration shape to aerodynamic performance.

CONCLUDING REMARKS

The last decade has been an exciting one for researchers in computational aerodynamics. The next one promises to be just as exciting for aircraft designers. Advances in computer power, solution algorithms, viscous flow simulation, and grid generation will permit much more detailed simulations of complex aerodynamic phenomena and the effects of geometry. These simulations will broaden to include other aeronautical disciplines, such as structures and propulsion. A new generation of managers will be in place, who, unlike their predecessors, have grown up with the computer. Their challenge will be to integrate the major computational advances of the 1980s into the design process in bold and imaginative new ways.

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16. Abstract

In the last decade, advances in computer technology and data communications began to drastically change the way we live and the way we work. We bank, shop, make airline reservations, and pay our bills by using computers. Now, a new generation of children is growing up with computers in their homes and in their classrooms. This computer revolution has also had a major effect on the production of new aircraft. With the major investment of the aircraft industry in computer-aided design and computer-aided manufacturing (CAD/CAM), much of the development process from design through manufacturing is computer controlled. Furthermore, great progress is being made in computerizing the aeronautical disciplines that are the elements of design, such as aerodynamics, structures, guidance and control, and propulsion.

Nowhere has this progress been more exciting than in aerodynamics. The availability of modern supercomputers and the ingenuity of computational aerodynamics researchers have resulted in new methods for solving historically intractable nonlinear flow-field problems. Advances in data communications have facilitated remote access to these large computing engines, and advances in computer technology incorporated in mini- and midicomputers now provide sophisticated interactive graphics and data manipulation capability. All of these advances have profoundly affected the aerodynamic design process.

Here we assess the changing role of computational aerodynamics in design and consider the prospects for continued advancement.

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