ICAS-88-4.8.4

MANAGING CFD IN INDUSTRY

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Abstract

The rapid growth in complexity of CFD now requires specialized theoreticians and applied mathematicians for code development. End users often find they must attend to mechanics of the code instead of being able to concentrate on the physics of the flow. Boeing has evolved a CFD applications support group to bridge the gap between code developers and project engineers. High-performance graphics workstations, quick access to supercomputers, and a management style that promotes CFD as an efficient and reliable tool are essential to the success of this approach. This paper discusses the evolution of CFD codes from research to application and identifies the roles played by the developer, the applications specialist and the code user. Several brief examples of successful CFD aerodynamics applications are included to illustrate the benefits achievable from a CFD analysis. Future requirements for CFD applications are discussed to point out the need for improved CFD management in the aerospace industry.

1.0 Introduction

Over the past decade computational fluid dynamics (CFD) has assumed an increasingly important role in the design of airplane configurations. It has become an integral part of the aerodynamic design process, standing beside the wind tunnel and flight test in importance.

Traditionally, the wind tunnel has supplemented flight test for measuring separated flow phenomena, as well as lift, drag, and other overall performance characteristics, and for exploring steady-state and oscillatory aerodynamics and flutter characteristics. Now, CFD, in turn, supplements the wind tunnel. By producing finely detailed descriptions of physical flow, CFD can predict phenomena that may otherwise be unobservable. In a few instances where the wind tunnel could add no essential data, component designs have even been released to fabrication on the basis of CFD data alone.[1,2]

Such reliability has been achieved through orders-of-magnitude increases in the ability of CFD to model flow physics and aircraft geometry. This complex modeling is the province of code developers, usually applied mathematicians, who specialize in that area. However, as the ability of CFD improved, a new problem was created. An ever-growing knowledge gap now exists between the developer of the code and the aircraft designer, with neither having a clear understanding of the other's concerns. Today, one of the greatest challenges in using CFD is to turn a research or pilot code into a practical engineering tool.

CFD produces overall cost savings by reducing risk in aerodynamic design, but the process is not cheap. Code development can be laborious, and its real value to industry does not become apparent until the application to the company product line. CFD may be unaffordable, or appear so to the user, if it remains laborious to apply. Too often, an analysis done for an engineering project requires a handcrafted solution that takes weeks or months to set up and hours of supercomputer time to execute. It also requires a code developer's participation and considerable time and graphics simply to interpret the numbers. The entire process is so laborious and complex that it is not uncommon to write a scientific paper devoted to one or two such solutions.[3]

In an industry environment, successful CFD applications require the timely availability of correct output data and representation of that data in easily understandable form. High-performance graphics workstations that can be used to create the geometry definitions, extract the computational models, and view the results from the CFD solutions are essential. Their function in the CFD process is illustrated in Figure 1.

The geometry systems used in CFD, engineering, and manufacturing must be compatible to ensure easy, rapid, and accurate transfer of geometric data between disciplines. To take advantage of the people skills, the high-performance workstations, the supercomputers, and the cooperative work with other facilities require a comprehensive communication network like the one in Figure 2.

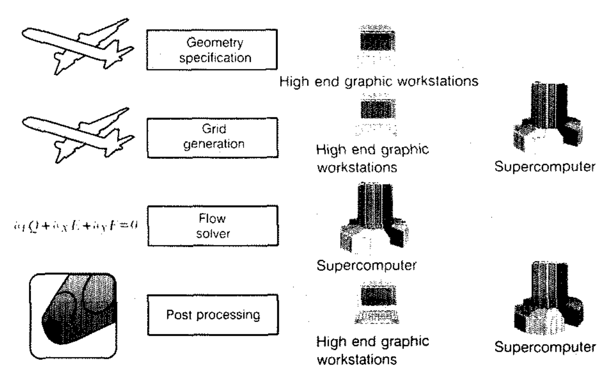


Figure 1. Elements of Computational Fluid Dynamics (CFD)

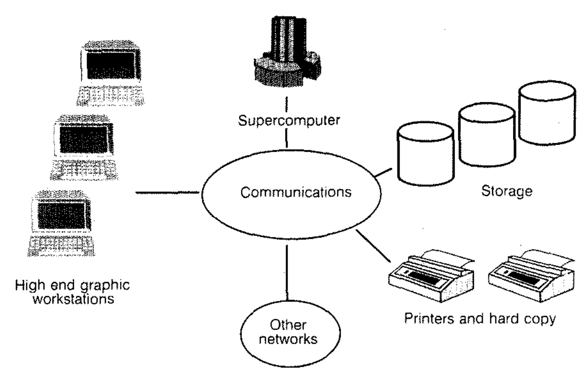


Figure 2. CFD Computer Network

The importance of high-speed communications is best illustrated by Figure 3. The transmission rates shown are the maximum or instantaneous rates; the actual or effective rates are much lower. The three file sizes shown are 1 Mbyte (one million bytes), which might be representative of the surface flow quantities on an aircraft configuration or a three-dimensional field grid; 100 Mbytes, which might represent the flowfield solution about an aircraft; and 10 Gbytes (ten billion bytes), which would represent the flowfield solution from a large unsteady flow that varies in time. During the 1970s, typical transmission rates were 1200 to 9600 baud (bits per second). These rates were barely adequate for the transmission of the surface flow properties from supercomputer to graphics site. When combined with the processing required to display the results, it was generally impractical to view more than one case per day. Today, 56K-baud (56,000-bit-per-second) transmission rates combined with high-performance graphics workstations are quite adequate for viewing surface property results if several users do not have to share the same graphics equipment and transmission line. The transmission of a flowfield solution is still very time consuming. At 50 Mbaud (50 million bits per second), the transmission rates are no longer the limiting factor for processing surface or flowfield results from steady flow cases. The human now becomes the limiting factor. In the future, transmission rates in the billions of bits per second and graphics workstations with near supercomputer capability will be necessary to view large unsteady flow solutions in near real time.

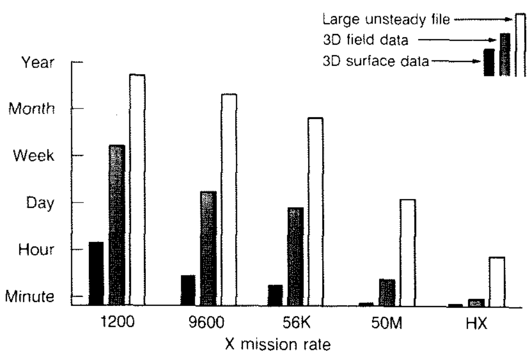


Figure 3. Data Transmission Times

Finally, there must be strong and enlightened management. The applications environment is unlike the research environment, where a good managerial approach is to provide the resources, then stand out of the way and let invention happen. Instead, applications support requires active planning and impetus for maintenance, enhancements, and consultation. The following objectives must be promoted:

a) The user must be provided with reliable service and maintenance. When a code "breaks," he must know whom to contact to get it fixed. The fix should be timely.

b) Product support must be very strong. The user must know where to call for help on the appropriate application of the theory behind the codes and the help must be available.

c) There must be a continuing product improvement program. A regular dialog between users and developers (moderated by the applications people) uncovers many new opportunities for improving all aspects of the CFD process. Continuing product improvement must become a way of life.

d) User training must be available.

Clearly these objectives require personnel whose daily work is more than generating code. After experimenting with an organizational structure where such personnel were ancillary to the code generation process, Boeing has found that the three-part structure in Figure 4 works best. The basic code generation is done by the CFD Methods Development group. The CFD Applications Support group serves as a technology/problems bridge between the project engineering groups and the code developers.

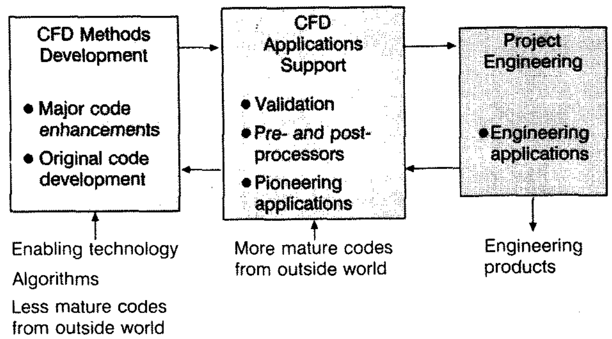


Figure 4. CFD Functional Environment

CFD Methods Development is staffed with CFD researchers who are skilled in the component technologies of CFD, namely flow solvers of various types, grid generators, etc. They produce the stream of new CFD opportunities and component codes. Their raw material consists of information (acquired primarily at scientific meetings), less mature codes acquired from elsewhere, and component codes built in house using either contract or inhouse funding.

CFD Applications Support comprises personnel with two different skill types, those who understand flow physics and those who understand computers. This group also has much of the expertise in CFD systems that glues together the component flow solvers, geometry systems, pre- and postprocessing, graphics, and whatever else is required to solve an engineering problem with CFD. Their raw material mainly comprises existing CFD systems and new component parts, which are disassembled, reassembled, and remodeled as needs and opportunities dictate.

The Methods Development group and the Applications Support group are equally important arms of the CFD organization at Boeing. In addition, the involvement of the project engineers is crucial in getting CFD technology accepted because these are the people who will apply CFD to the company's product line. The real value of CFD is realized when it can be used as an everyday tool to produce a better product. Management's role is to find the most cost-effective engineering solution, considering both cost and quality, and to determine the appropriate mix of CFD and experiment to produce that solution.

2.0 Organizing for Effective Applications

2.1 Elements

The major elements in industrial application of CFD are threefold: the tools (software and hardware), the people, and the interfaces between them.

Like many new technologies, CFD software was for some years an esoteric specialty. The first generation of panel methods, typified by Reference 4, required such highly trained and experienced users that some engineers at Boeing made full-time careers of setting up problems for that code.

A second-generation algorithm that is more mathematically robust, as embodied in the PAN AIR panel method[5,6], was designed to overcome many of the limitations of the first-generation codes. The training time was less, the level of knowledge required to ensure a properly posed problem was vastly reduced, and the problem setup time was shorter.

The CFD hardware has also gone through generations of improvement. In the early years, the primary equipment bottlenecks were the limited memory and processing speeds of the "supercomputers." More recently, as supercomputers have become larger and faster, communications and graphics have emerged as the bottlenecks to the development and use of CFD. Today it is possible to compute a flowfield in minutes but then take hours to transmit the data over the lines to a workstation or remote job entry site. And without high-powered graphics, the output may be too difficult for anyone to understand.

The people involved in the process have raised their capabilities and awareness. Project engineers and managers have improved their understanding of the elements of CFD. They are better able to translate the results of a computation in terms of what it implies about the behavior of the real flow. The key ingredient in attaining this understanding has been continuing education by CFD management. The transition has been similar to the process in which aerodynamicists long ago became accustomed to the translation between wind tunnel and flight data (involving items such as Reynolds number scaling, wind tunnel wall interference, and model support interference). We must realize that a comparable set of translation skills involving computation is required of today's practicing aerodynamicist. The pace of development of new computational capabilities is accelerating, and project engineers are hard pressed to acquire the computational knowledge they need to be effective, intelligent users of a rapidly expanding array of new codes.

A logical response to this acceleration was to establish an applications group of trained personnel to work on analysis and interpretation of new codes. CFD can be run by the project engineers themselves, and, in fact, they must if CFD is to be a practical industrial tool[7]. As codes mature, the applications group educates the project engineers to run them with minimal assistance. The applications group then turns its research and interpretation focus to codes that are still on the boundary between expert and nonexpert use. Thus the range of an application group's work is always shifting.

The challenge to the applications group manager is to provide the best resources and to maintain the interfaces that keep the group operating efficiently as a team. Specifically, the manager must—

a) Recruit the right people.

b) Provide them with convenient access to state-of-the-art computing equipment without crunching scarce resources.

c) Calibrate and validate the results to produce a code that provides production-level dependability.

2.2 Tools

CFD software today covers a wide range of capabilities in terms of the complexity of computational flow physics and configuration geometry. In a perfect world, our CFD codes would be able to solve the Navier-Stokes equations over any type of geometry without introducing numeric artifacts. The simulations would be perfect in representing the fluid flow and could be accepted at face value. However, such is not the case today. The computers are neither big enough nor fast enough, and our algorithms make too many approximations. Figure 5 illustrates the limit of what we at Boeing believe is currently practical for air transport designs. This limit is being continually challenged by researchers here and abroad.

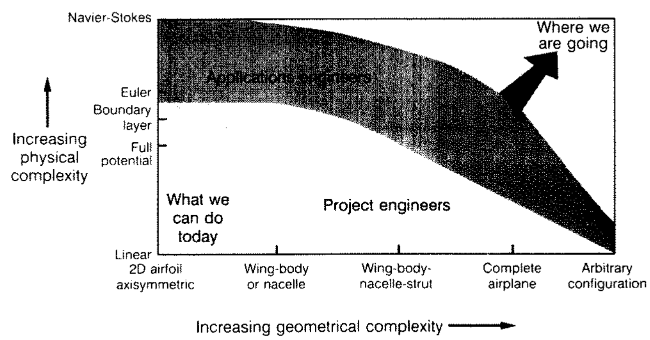


Figure 5. Status of CFD for Design Applications

Not all this technology, of course, is at the same level of maturity in terms of production usability. This is illustrated in Table 1, the

Production codes	Formulation	Geometry capability
A502/PAN AIR	Linear potential	General geometry
A488	Conservative full potential with coupled 3D boundary layer - analysis	Wing-body Wing-body-strut-nacelle
A555	Conservative full potential with 3D boundary layer - design	Wing-body Wing-body-strut-nacelle
A585	2D Euler with coupled boundary layer	2D airfoil
A588	3D Euler with coupled boundary layer	Isolated turbofan nacelle Isolated turbofan nacelle-strut
P318	Axisymmetric full potential with boundary layer	Isolated axisymmetric nacelle
P467	Full potential with 3D boundary layer	Axisymmetric nacelle
P582	Full potential	General geometry
WBPPW/BOPPE	Extended transonic small disturbance with coupled boundary layer	Wing-body-strut-nacelle-winglet
Expert user codes		
	Euler	Wing-body-tail Wing-body-tail-aft propfan UDF nacelle-strut Turbofan nacelle
	Euler with coupled 3D boundary layer	Wing-body-tail Wing-body-strut-aft propfan Wing-body-winglet
Emerging code		
TRANAIR	Full potential	General geometry

Table 1. CFD Toolbox

current Boeing "toolbox" of CFD codes. Those classified as production codes are in wide use throughout the company by a variety of CFD users. They are well documented, have been specialized to a certain extent, and can be run by nonexperts. The second class, expert user tools, comprises codes that may have more general and advanced capabilities but are not as well developed; they require special skill and the help of the applications group to run. Most of the production and expert user codes can be classified as either "validated" or "calibrated" codes.

A validated code is one for which the physical domain to which it can be applied is well known. Validated codes can usually be run in black box fashion, where the user need only follow well-established guidelines to produce a solution of known validity. Most, but not all, production codes are classified as validated codes.

We also have calibrated codes, which usually treat more complicated physics and rely on more empirically derived approximations (such as turbulence modeling) in their formulation. A calibrated code thus depends more on adjustments to produce a solution. These calibrations can be adjusted to improve agreement with experimental data. Most of the expert user codes are calibrated codes.

The emerging codes are new technologies under development that offer new capabilities and may become production tools in the near future. Currently these codes are neither calibrated nor validated.

In looking for codes to mature, the applications group finds it just as important to integrate finished algorithms from outside sources as to develop Boeing inhouse products. This flexibility is important to achieving the optimum combination of capabilities and is one major reason why applications cannot simply be an adjunct of code research and development.

2.3 CFD Development Phases

To provide a foundation for describing the management changes that have accompanied increasing use of computational aerodynamic methods, let us review the key steps or phases involved in the development and application of the software tools. Figure 6 identifies five distinct phases in the development process. Phase I produces enabling technology—algorithms and such—that provide a basic means to solve a given problem.

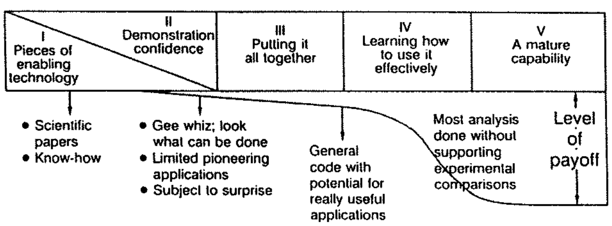


Figure 6. The CFD Development Cycle

Phase II, which overlaps Phase I, comprises the initial attempts to explore, validate, and demonstrate a new computational technology. One usually observes some limited pioneering applications at this stage, but this emerging technology is not yet at a state that will produce significant payoff or impact because the technology is still subject to surprise. Hence, managers and design engineers are unwilling at this point to make important standalone design decisions based on computed results. Standalone decisions do not happen until well into Phase IV.

Many of the codes developed by academia or with government money end in Phase II with a contractor report or scientific paper that proclaims, "Gee whiz, look what can be done." For many codes this is a natural transfer point for industry to assume responsibility for further development because most of what must occur beyond that point will be unique to the particular needs of each individual industrial organization.

Thus, the main outputs of Phase II are demonstrator codes combined with a vision of what is really needed. Phase III is aimed at supplying the substance of that vision and usually entails a generalization or other modification of Phase II codes combined with a coupling of front- and back-end interfaces to produce user-friendly, well-understood, and maintainable software that has a valuable new capability. At the end of Phase III, however, the contribution or impact of the code on the corporate bottom line is still minimal because engineers and managers don't yet understand how the existence of this new tool will change the engineering process and what it will be used for; they have yet to gain enough confidence to make important, standalone decisions based on the code. That takes time, exposure, and experience.

In the fourth phase, the impact or payoff of a code grows rapidly. In this phase project engineers, management, and researchers work together to learn how this new capability will enter into and change the aerodynamic design process. Needs for code refinements invariably surface, needs that were not anticipated and that must now be met by more algorithm research, additional geometry preprocessors, etc. Management in this phase has a difficult challenge to prevent stagnation or diversion of the capability. By the time software is in Phase IV, there is a tendency to believe it does not need further work. After all, it now executes properly and yields solutions that look right. Besides, there are now exciting new challenges that must be exploited (and funded). Without a deliberate effort to get the code through Phase IV, it may never be ready to deliver that value-added information that results in a better product. Instead, attempts to use the code on a time-critical engineering problem may bog down in frustration as project engineers try to get the code to work properly on the problem at hand.

Good applications group support allows a code to reach Phase V—a mature capability. In Phase V, the requests for additions or refinements have diminished to the point where the code (like the Boeing production codes in Table 1) has settled down to occupy its rightful niche in the toolbox, and project engineers and managers have learned its capabilities, limitations, and rightful applications. Phase V codes are characterized as follows:

a) They are used outside the research organization that created them.

b) Their documentation is adequate to allow use by someone other than their creators.

c) Stable versions that are not undergoing constant change exist for use outside the research environment.

d) Sufficient validation has been demonstrated that outside users are willing to invest the necessary effort to use them.

Production codes must include geometry tools because these are essential for the preparation of the inputs to the various CFD codes. In addition, three-dimensional graphics running on suitable workstations allow the inspection of surface and field grids prior to execution and provide the keys to understanding the frequently massive output from a typical CFD solution. Thus the timeliness of CFD is heavily tied into the quality of the geometry and graphics tools available. The primary tool that fits this need at Boeing is the interactive, three-dimensional geometry system known as the Aero Grid and Paneling System (AGPS)[8]. The value of a geometry system that can properly support the needs of the CFD community while providing a proper tie-in with manufacturing cannot be overstated.

2.4 Key Personnel

The emergence of CFD at Boeing has led to the evolution of certain key roles or skills that we have been discussing in this paper: namely, the algorithm researcher, the applications engineer, and the project engineer (fig. 7). Each of these has a role dominating one or two of the development phases (as charted in fig. 6), and each also contributes to several other phases. One individual may assume several of these roles during the evolution of a computational capability.

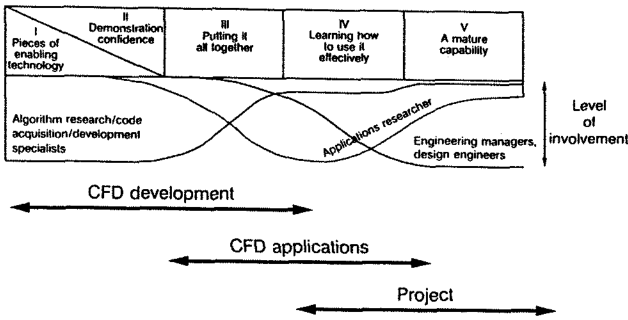


Figure 7. Key Player Roles

The skills required of today's algorithm researcher are vastly different from traditional aerodynamics. The most important skills are strong mathematics and a thorough knowledge of the computer. The goal is to find a way to solve a given, known partial differential equation or equations, usually cast in terms of a boundary value problem, and demonstrate solution procedures that are stable, accurate, and reliable. It makes little difference whether these equations describe fluid flows, electromagnetics, or acoustics. An example is the development of TRANAIR, which provides a common framework for solving problems in these three disciplines[9]. A knowledge of the language and key terms encountered in traditional aerodynamics is useful in helping algorithm researchers communicate with the other players in the code development process but that portion of the work involving physical understanding and modeling is mostly dealt with by the applications engineers.

The applications engineers are the link between the algorithm researchers and the project engineers. The right people for this role are those with broad backgrounds, who understand both the needs of the project engineers and the language of the algorithm researchers. They must have a good feel not only for the computational methods, but also for the experimental test data and the geometric description of the subject. Most of the applications engineers' efforts focus on Phase IV, where they work closely with the algorithm researchers, correcting software errors and calibrating the code, and with the project engineers, ensuring that the code will meet their needs.

Phase V requires managers and project engineers who have at least a conceptual understanding of a code's underlying assumptions and inherent strengths and weaknesses. They must have this knowledge to extract the value from the CFD technology when it becomes a mature capability. They are also involved in Phase IV, learning about the code and developing the confidence to make decisions based on computed results.

It is important to recognize the overlap of roles in Figure 7. Both the applications engineers and key project engineers must be "validated users" who understand both the anticipated flow physics and the limitations of the codes being used. They both must know how to interpret the solutions in light of the code's limitations—what can and cannot be believed about the solution.

Even though the contribution of a particular role or skill may be minimal in some phases, its presence is usually essential. One common example is the presence of algorithm research skills during the applications endeavor of Phase IV. Invariably, questions concerning the code arise that can best be answered by the algorithm researcher. And, invariably, needs arise for a number of algorithm improvements before the code grows to be truly effective in the role identified for it during Phase IV. Thus it is essential that organizations that seek to use the newer codes have access to and control over staff who have algorithm research skills.

Thus, computational aerodynamics has had an impact not only on the aerodynamic design process, but also on skills, people, and organizational structures. We now have a toolbox of flow solvers running the gamut from linear potential solutions to Navier-Stokes, geometric tools ranging from simple line fairing to lofting of complex surfaces, and a user base with an experience range from those newly graduating up to those who have considerable wind tunnel experience. The management trick is to marry and focus these capabilities to solve practical problems. We find computational skills to be of increasing value throughout aircraft design organizations. Chief engineers in the Boeing Commercial Airplanes division are aware of today's basic issues in computational research and frequently suggest computation-based approaches to problem solving. Formal systems, boards, and committees are in place for such tasks as software version control, software maintenance standards, and change requests, and upper-level management has made major computer hardware acquisition decisions.

2.5 Interfaces

The most serious barrier to making aerodynamic computer programs useful is in the area of engineer-software interface. From the engineering user's viewpoint, the development of program interfaces and pre- and postprocessing capability for new computational methods is just as important as the primary algorithms and machine architecture. As new methods to compute more details of the flowfield are developed, the comprehension of output data becomes a major problem. This problem is doubled when design capability is added to a method.

To provide a better computing environment for the CFD Methods Development and Applications Support groups, Boeing created a CFD Laboratory in 1987. The lab hardware is closely patterned after the architecture of the Numerical Aerodynamic Simulator (NAS) at the NASA Ames Research Center, which served as a pathfinder for the Boeing facility. As with the NAS system, direct access to supercomputers, high-performance graphics, high-speed communications, and advanced operating systems are a fundamental requirement. The new Boeing facility links high-powered graphics workstations and high-speed communications equipment (50M baud) directly to a Cray X/MP supercomputer in the same building. Communication with the supercomputer is through a high-speed network that supports both batch and interactive processing.

At the lab, graphics workstations provide job preparation and postprocessing capabilities. Interactive color graphics provide an excellent vehicle for the review of calculated flowfields and animated displays of the solutions as they evolve. The workstations also provide access to color printers, laser printers, film recorders, video recorders, and disk storage. In addition, the lab is connected directly to the rest of the Boeing facilities and to the NAS facility by a high-speed (56-K baud) data transmission line.

This combination of direct access to advanced computing facilities, together with the unique tools provided by Boeing-enhanced operating systems and software, provides an especially productive environment for both researchers and applications engineers. The researcher, using fast turnaround from the supercomputer combined with the interactive display capabilities of the workstation, can test new ideas rapidly by using realistic problems and then visually detect areas requiring attention. The applications engineer can inspect complex configurations and grids before beginning calculations and can obtain immediate pictorial understanding of the results. Visitor sites are maintained for the use of project engineers when access to communications, graphics equipment, and expert consultants is essential to timely CFD analysis.

2.6 The Future

In the past, 10 years was typically required for a new computational capability to be adopted by design engineers.

At Boeing, computational methods have become an integral part of the aerodynamic design process. Over the past several years we have made significant reductions in the flowtime required to make a new code available. We fully expect to continue the improvement. The major stumbling block in making computational aerodynamics an everyday engineering tool is in the user interface area. What we need now are—

a) Truly interactive computing with online graphic displays for input checkout and result analysis.

b) Automated interfaces between related computer programs used in the design process.

c) Faster design cycle times.

We are confident that these capabilities will make CFD a truly versatile industry design tool.

3.0 Examples of CFD Applications

This section cites some specific examples where CFD has had a well-defined impact on the design of recent Boeing aircraft. One point that has become evident over the years is that neither management nor the code developers can always anticipate the ultimate use to which the computational tools will be put. It is therefore wise to have a general-purpose toolbox of CFD codes.

3.1 Engine-Airframe Integration

In the mid-1970s, Boeing aerodynamics management made a long-term commitment to a joint CFD wind tunnel test program to improve our understanding of the interference drag of an underwing pylon-mounted engine nacelle. The state of the art at that time, achieved through many years of wind tunnel testing, is shown in Figure 8. Designers had found that if a nacelle was positioned so close to the wing as to appear outside the shaded area, the drag was unacceptably high. But wind tunnel testing, which had revealed the existence of this unwanted interference drag, had failed to identify its source.

The company funded a study focused on use of the wind tunnel and CFD in a complementary way. CFD modeling techniques would be developed to represent the nacelle installation on the wing. Wind tunnel testing would be conducted to provide detailed experimental data for validation of the CFD results. Once management was satisfied that CFD could adequately model the nacelle installation, detailed CFD studies would be conducted to determine the sources of interference drag. From these findings design guidelines would be developed to allow closer coupling of the nacelle to the wing[10].

The knowledge and computational experience thus obtained were subsequently applied to the design of the Boeing 757, 767, 737-300, and KC-135R nacelle installations, enabling very close-coupled installations to be achieved (fig. 8) without incurring a significant drag penalty. Without this understanding provided by CFD, some commercial transport programs would not have happened (fig. 9).

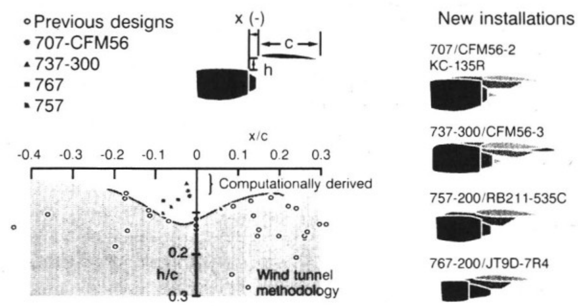
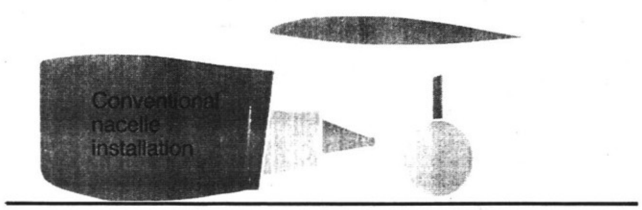


Figure 8. Computationally Derived Close-Coupled Nacelle Positions



"Without CFD there would not have been a 737-300 program."

Figure 9. Conventional Nacelle Installation on 737-300

3.2 Wing Design

In early 1987 a critical wing design activity within Boeing reached an impasse with regard to satisfying airplane performance requirements, wing structural requirements, and other practicalities necessary for a successful overall design. It was determined that a significant advance in the transonic technology level of the wing was needed. However, the wind tunnel schedule for the remainder of 1987 did not provide sufficient time to carry out the extensive testing needed if such an ambitious design program were to be undertaken using the standard approach.

Two-dimensional CFD analysis and design tools were used to develop a series of airfoils to investigate different pressure distributions consistent with this aggressive design philosophy. After a confirming wind tunnel test, three wings for a wing-body configuration employing variations of the most promising design pressure distribution were designed in a time period of a little over a month, using a system of viscous/transonic design and analysis CFD codes developed over the previous decade[2].

Wind tunnel tests, conducted in the fall of 1987, included the three new wings and a previously designed baseline wing. The analysis had predicted how the four wings would rank with respect to each other at the design cruise point. The wind tunnel test results confirmed the CFD predictions.

This endeavor was a success and was carried out in a very short time because of the skill of the responsible project engineers, the ability of the applications group to adapt existing code to the new approach, and because the necessary tools were in place.

4.0 Conclusions

From our experience at Boeing, we have seen that CFD can reduce the number of test configurations and iterations for a new airplane by approximately 80%. Some of this savings is then available to advance the design and produce a more cost-effective product. To a large extent, this is because of the flexibility CFD allows in changing design philosophy and allowing opportunity for innovative design and because of the confidence management has in our approach to using CFD.

A big management challenge that remains is to continue the integration of CFD into the design process. Today's codes can only deal accurately with the attached flow problems common to transport configurations in cruise flight. Even here, we find as we try to improve the accuracy of our CFD computations that we have reached the point where the experimental data normally used as a measure of confidence are becoming suspect. As we try to understand the flow in greater detail, wind tunnel testing and CFD are becoming more intertwined. They will become even more so as we extend our computational abilities into separated flows. We may find that there is not yet an adequate experimental data base to determine the proper turbulence model for use in a Reynolds-averaged Navier-Stokes solver.

Currently, CFD cannot predict many of the dramatic effects that flow separation can have on the handling characteristics of an airplane[11]. It is necessary to calculate the correct separated flow in detail if CFD is to be useful in dealing with problems such as pitch-up or directional stability at high angles of attack. Solving these problems will take a long-term commitment and will require an integrated approach using both CFD and tunnel experimentation.

The value of CFD to industry is in the application. Only through the application of CFD to the company's products can the expense of CFD be justified. Successful CFD applications require timeliness, understanding, confidence, and management commitment.

Timeliness means getting the CFD done in time to influence the design of the product. The use of the integrated hardware and software by knowledgeable validated users contributes to timeliness.

Without the understanding of the physics, CFD is just so many numbers. Extracting understanding from CFD computations through the use of high-powered graphics workstations is no longer a luxury, but a necessity. Confidence in the value of CFD on the part of the project engineers and managers can only come with extensive code validation. Without validation, CFD can produce only pretty pictures, not value-added results.

All of this takes management commitment: commitment to the code development/validation process; commitment to the proper skill mix of algorithm developers, applications engineers, and project engineers that are validated CFD users; commitment to rely on CFD for engineering design when economical; and commitment not to expect CFD to solve problems well beyond its capability.

Acknowledgements

The author would like to thank Edward N. Tinoco and Brian Roberts for their assistance in preparing this paper.

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