Impact of Computational Fluid Dynamics on Development Test Facilities

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The impact of computational fluid dynamics (CFD) on the traditional role of aeronautical ground test facilities over the next 15 years is assessed via a National Research Council study. More powerful scientific computers and more efficient numerical algorithms should result in the ability to practically compute the flowfield about a complete aircraft with the Reynolds-averaged Navier-Stokes equations at a unit cost three orders of magnitude lower than at present. No dramatic change in the cost of testing in ground facilities is foreseen because more efficient computer-enhanced facility operation is partially offset by increased power and labor costs. From the user viewpoint, the risk in development of a new aircraft or engine is so great that use of proven methods of verification by means of test facilities will not change significantly. In the next 15 years CFD and ground test facilities will be utilized in a complementary rather than competitive mode of obtaining design data and the end result will be a better product.

Introduction

SIGNIFICANT advances in computational fluid dynamics (CFD) as a result of improvements in numerical algorithms as well as in processing speed and storage capacity of new generations of computers make CFD an ever more powerful tool in the aerodynamic design of aerospace systems.

In order to obtain design data, how are developments in CFD likely to infuence the traditional role of conventional aeronautical ground test facilities over the next 15 years?

This is the question addressed by an ad hoc committee of the National Research Council's Aeronautics and Space Engineering Board. The areas of expertise represented on the ad hoc committee included airframe and aircraft engine design, computational fluid dynamics, turbulence modeling, computer architecture, and wind tunnel technology. Its membership included Chairman Ronald Smelt, Lockheed Aircraft Corporation (ret.); Richard Bradley, General Dynamics Corporation; Dean Chapman, Stanford University; Sidney Fernbach, consultant to Control Data Corporation; Grant Hansen, Systems Development Corporation; William Heiser, General Electric Company; Stephen Honig, Grumman Aerospace Corporation; Mark Kirchner, Boeing Commerical Airplane Company; Robert MacCormack, University of Washington; Alojzy Mikolajczak, formerly United Technologies Corporation; Eli Reshotko, Case Western Reserve University; and William Reynolds, Stanford University. The present author participated in the capacity of Study Director.

Some of the key results of this National Research Council (NRC) study[1] are reflected herein. Earlier projections in CFD and test facilities were given, respectively, in the 1979 Dryden Lecture by Chapman[2] and the 1978 Guggenheim Lecture by Smelt.[3]

Projections for CFD

Chapman[2] identifies four stages of development which characterize advances in computational fluid dynamics. These stages, along with two important substages, are given in their order of evolution in Table 1.

Stage I allows the computation of attached flow over slender bodies at small angles of attack at subsonic and supersonic speeds. Pressure distributions, lift, subsonic induced drag, and supersonic wave drag can be computed.

Stage II removes the restriction to slender bodies and extends the computational capability to the transonic and hypersonic regimes. Substages Ia and IIa include boundary-layer codes allowing for the computation of skin friction drag and improved pressure distributions.

Stage III includes all of the terms in the Navier-Stokes equations; however, those terms representing the time-averaged transport of momentum and energy by turbulence are modeled semiempirically. Stage III will provide the additional capability to compute separated and interacting flows, flows at large angles of attack, and some forms of unsteadiness.

In Stage IV—the full Navier-Stokes equations—the dominant turbulence transport terms are directly computed while small-scale turbulence is modeled. Stage IV will make possible computations of boundary-layer transition, aerodynamic noise, and turbulent intensities.

Status of Stages

What is the present status of these stages?

Stage I is essentially mature and, along with Substage Ia, has been widely used in aircraft design for over a decade.

Stage II has been in limited use in aircraft design since the late 1970's and, with the computer power presently

Table 1 Stages of development in computational fluid dynamics

Stage	Approximation
I	Linearized inviscid
Ia	Linearized inviscid plus boundary layer
II	Nonlinear inviscid (Euler)
IIa	Nonlinear inviscid plus interacting boundary layer
III	Reynolds-averaged Navier-Stokes
IV	Full Navier-Stokes (large eddy simulation)

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available—CRAY 1, Cyber 205—and perfected automatic grid generation, is expected to reach maturity in the 1980's. Figure 1 illustrates a Stage II computation (TAIR inviscid code) and the addition of a Stage IIA viscous correction, compared with wind tunnel measurement for the pressure distribution over a supercritical airfoil in the transonic regime. Note the local supersonic region on the expansion side terminating in a weak shock just beyond midchord.

Stage III is presently in an intensive research and development phase for simple geometric configurations. Figure 2 illustrates a Stage III computation of density contours over an axisymmetric conical afterbody containing a centered propulsive jet in a supersonic stream and comparison with experimental flow visualization. With projected new supercomputers and improved numerical methods, Stage III is expected to come into limited design use by the end of the 1980's, and into full use in the 1990's.

Stage IV, presently in its very early pioneering research phase, is expected to enter an extensive research and development phase at the end of the 1980's, but may not be used significantly in practical applications before the end of the 1990's. It needs much more powerful computers than presently available.

It is clear that the next major step in advancing computational fluid dynamics is Stage III. Its introduction into the aerodynamic design process is dependent on 1) the development of effective applicable turbulence models, 2) perfecting automatic grid generation for complex geometries,

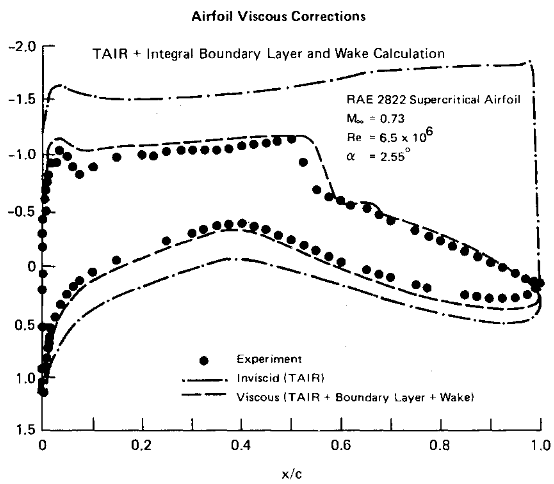

Fig. 1 Comparison of measured and computed pressure distribution over RAE 2822 supercritical airfoil (courtesy NASA/OAST).

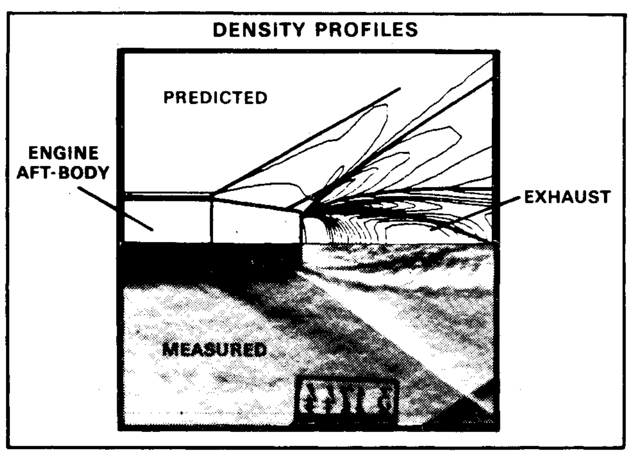

Fig. 2 Computed density contours over axisymmetric engine aft body with jet exhaust in a Mach 2 stream compared with experimental features from schlieren photograph (courtesy NASA/OAST).

3) the development of more powerful scientific supercomputers, and 4) the development of more efficient numerical algorithms.

The automatic generation of grid systems around complex aircraft configurations is currently receiving much attention.

With regard to turbulence, while significant progress in its modeling has been made in the past decade and should continue, the physical phenomena are so complex and varied that adequate modeling for all cases of practical interest is not anticipated in the next 15 years. Thus, the main limitations of computational fluid dynamics with Stage III are expected to be due to inaccuracies in turbulence modeling.

Development in Supercomputers

What rate of progress in supercomputer development can we expect in the next 15 years?

While the U. S. dominated the field from the time the electronic computer was invented, its rate of progress in scientific supercomputer development has slowed in recent years due largely to the shift in the market to business, industrial, and personal computers. Not suprisingly, strong foreign competition has emerged, notably from Japan.

Fujitsu and Hitachi have recently introduced supercomputers reportedly more powerful than any U.S. computer presently available. Furthermore, the Japanese Ministry of International Trade and Industry (MITI) plans to develop a high-performance scientific supercomputer utilizing new component technology and architecture to achieve a performance target of tens to hundreds of BFLOPS (billions of floating point operations per second) by the end of the 1980's. The MITI performance goal exceeds that of the NASA Numerical Aerodynamic Simulator—1 BFLOP—which will use proven component technology to minimize risk.

If the MITI project is successful, it could have a profound effect on computational applications in the 1990's. However, even with present and foreseeable silicon semiconductor technology computer speed and memory can be increased by several orders of magnitude before physical limitations arise. Improvements will evolve from progressive increases in the density and area of silicon microelectronic chips.

An estimate of the growth in computer speed in the next 15 years based on information from U.S. and Japanese major supercomputer manufacturers is given in Fig. 3. The estimate assumes continued use of silicon technology throughout the period. Computer memory size follows roughly the same trend as speed—the order of 10^5 words of memory per

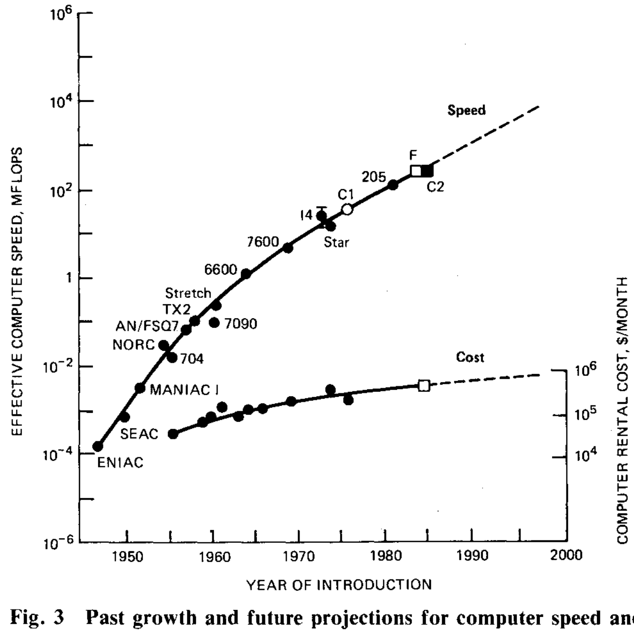

Fig. 3 Past growth and future projections for computer speed and computer cost.

MFLOP (millions of FLOPS). By the late 1990's it is projected that computer speed will rise to about 10^4 MFLOPS and memory size to about 500 megawords through use of 1-megabit memory chips.

In spite of the tremendous growth in performance over the years, the cost of computers has barely increased beyond inflation. Past and projected trends in monthly rental cost are also shown in Fig. 3. The actual cost of a computer is very roughly 40 times the monthly rental. While the cost has increased tenfold since the mid-1950's, speed has increased by 10^4 for a net increase in computer cost effectiveness of 10^3. In the next 15 years a further improvement in cost effectiveness by a factor of 30 can be expected.

Developments in Numerical Methods

The present status of computational fluid dynamics in terms of the stages of development was discussed earlier. Major advances in the years ahead will come from Stage III. In order to resolve the flowfield about a complete aircraft configuration by numerical solution of the Reynolds-averaged Navier-Stokes equations about 2 to 9×10^6 grid points with 15 to 30 words of computer memory per grid point would be required.

The grid system would consist of component grids to resolve viscous effects locally in the near field, interfacing with an outer stretched grid extending far away from the aircraft where the flow is essentially inviscid. Procedures to match boundary conditions between the separate grids are being developed and are expected to be ready within the next few years.

Stage III calculations by implicit methods presently require several thousand iterations to converge but are continuing to improve. Also, multigrid procedures presently under intense study show great promise for accelerating convergence and improving the efficiency of numerical methods for the Reynolds-averaged Navier-Stokes equations by nearly two orders of magnitude.

With the computers and numerical methods expected to be available in 5 years it should be possible to perform a Stage III research calculation of the flow about a complete aircraft configuration at flight Reynolds numbers. Another 5 to 10 years of development will be needed before this type of calculation reaches maturity for aircraft design use.

Past and projected improvements in efficiency of numerical methods are reflected by the curve in Fig. 4. Combining these improvements with projected improvements in computer hardware gives the trend in relative cost for computing a given flow with Stage III, shown in Fig. 5. As seen, over the next 15 years this cost is projected to drop by three orders of magnitude.

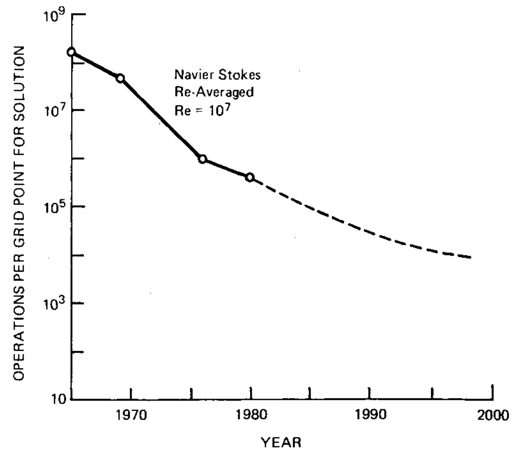

Fig. 4 Past and projected improvements in efficiency of numerical methods.

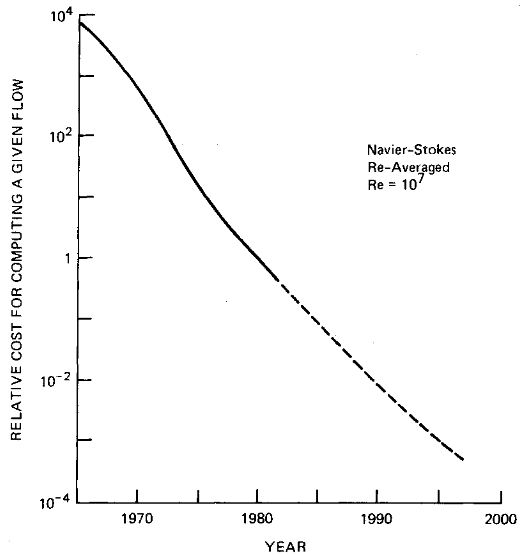

Fig. 5 Past and projected decreases in relative cost of numerical computations for Stage III considering improvements both in computer hardware and numerical methods. Cost normalized to 1980.

Test Facility Developments and Needs

While great strides will be made in CFD, improvements and advances are taking place in ground test facilities. Although neither ground test facilities nor CFD provide a perfect answer to a designer's needs, each offers certain advantages discussed further on, which merit exploitation. The designer will use the best possible, and not necessarily the least costly, mix of the two methods.

Computer Enhancement of Test Facility Performance

An important development in ground test facilities is the use of computers in general and CFD in particular to enhance performance. Three critical areas in wind tunnel or engine testing that can be improved by computational means are data quality, operational efficiency, and simulation of the flight environment.

Data quality improvements can be achieved by CFD calculations for pretest selection of model sizes and flow conditions, and posttest confirmation of data accuracy or identification of unusual results and discrepancies.

Operational efficiency improvements have already been achieved via the computer by such techniques as on-line processing and displaying of raw and analyzed data, and programmed control of model and instrumentation attitude and position. Such computer-enhanced operation has considerably reduced test time. It is expected that CFD in the long term will have a strong influence on the planning and operational philosophy of ground testing.

Simulation of the flight environment in ground test facilities has been improved through a number of computer-based methods such as captive trajectory system testing—e.g., for store separation—and extrapolation of data to flight Reynolds numbers. Future uses of CFD for flow simulation improvement include the interactive control of the geometry of adaptive walls in transonic wind tunnels in order to eliminate their interference.

Specific areas in which continued improvements will arise from the application of computers to ground testing include closed-loop model controls, computerized tunnel controls, data corrections for interference effects, and data automation.

All of these improvements in the efficiency of ground development facilities will clearly result in considerable shortening of the time required to perform a given test. In fact, some of these improvements are already in use as noted. While substantive cost savings per test program might be anticipated, they are not likely to be achieved because of increased energy and labor rates.

Test Facility Requirements as Influenced by CFD

Confidence in the use of CFD for design will depend on its proven ability to give reliable and accurate aerodynamic information. Verification of the validity of CFD results in the next 15 years will depend largely on comparisons with data from ground test facilities, thus giving the latter an important additional role to that of providing direct design data.

There will be a need to verify CFD Stage III—Reynolds-averaged Navier-Stokes—over a broad range of flow conditions up to flight Reynolds numbers. Although the latter requirement exceeds the limits of currently operating wind tunnels, the NASA National Transonic Facility (NTF), soon to be operational, will have the needed high Reynolds number capability.

Turning now to design verification needs in the next 15 years, new aircraft programs will require an expanded flight envelope, particularly in angle of attack and yaw. This requirement severely limits model size for test facilities and strains the capability of Stage III computational methods. However, the modified 80×120 ft full-scale tunnel at NASA Ames Research Center and, at higher speeds, the NTF may be able to provide data at high angle of attack without severely compromising Reynolds number despite smaller than usual model sizes.

With regard to the more demanding requirements for V/STOL aircraft, it appears that neither test facilities nor CFD will be adequate to the task within the next 15 years.

As for propulsion systems, ground testing of large and more powerful aircraft engines, and the integrated performance of engine/airframes will be possible when Arnold Engineering Development Center's (AEDC) Aeropropulsion Systems Test Facility (ASTF) is completed and becomes operational. Since engine test programs generally combine aerodynamic measurement and verification of life, transient response, and emissions it is not likely that the need for experimental facilities will be reduced by CFD developments in the 15 years ahead.

User Viewpoint

To put into perspective the aerodynamic design verification phase of a new aerospace vehicle, one has to view it in relation to the total vehicle development requirements. An extensive survey of economic and technological factors in aeronautics is given in the excellent and still topical 1974 Wright Memorial Lecture by Flax.[4]

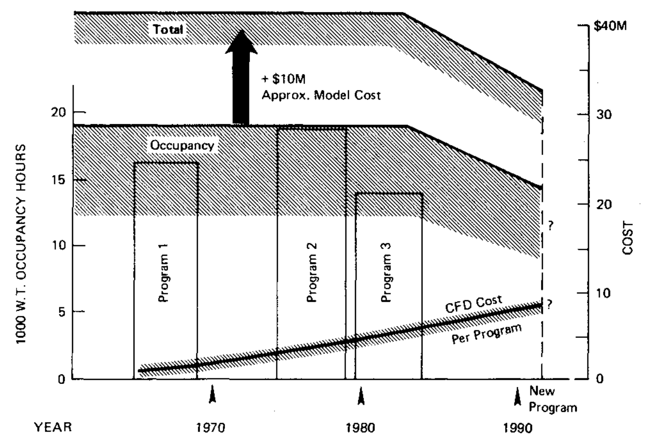

Fig. 6 Wind tunnel and computational fluid dynamic costs for a typical commercial transport development program (1981 dollars).

Typically, major aircraft programs in the past decade have incurred development costs between $1 and $2 billion, so large as to be on the order of the net worth of the manufacturer, leading to the oft-heard expression "you bet your company."

Of the development cost, wind tunnel occupancy time for design verification has typically been between 10,000 and 20,000 h which, at an average cost of roughly $1500/h, totals between $15 and $30 million for each program. Wind tunnel models add roughly another $10 million. Figure 6 shows actual wind tunnel occupancy hours and costs, and CFD costs incurred by a major aerospace company for design verification of three commercial transport aircraft, along with its projections of such cost trends into the 1990's. Thus, design verification represents about 2% of the cost of development of a major aircraft program. Similar costs are incurred in propulsion system development.

With the enormous financial investment involved, the designer's objective is to reduce the risk at the earliest possible phase of development, and he is not likely to change from tried and proven verification methods until equal confidence in new techniques has been built up, but he will use all the design capabilities available to him. Thus CFD as a new technique will be used to complement design data obtained from ground test facilities. In fact the two techniques have somewhat different roles and, indeed, different strengths and weaknesses as discussed below.

CFD as a Design Tool

CFD methods have already seen some degree of use by industry, along with ground test facilities, to aid in the configuration design of transport and military aircraft, helicopters and other V/STOL types of aircraft, airbreathing missiles, re-entry missiles and spacecraft, as well as propulsion systems.

Specifically, CFD has already been used in aircraft design for subsonic and supersonic inviscid flowfields around simple three-dimensional shapes, two- and three-dimensional transonic inviscid flowfields, the addition of boundary layers and separation criteria, and two-dimensional subsonic multielement airfoil configurations (high-lift devices extended) with boundary-layer and separated wake simulation. These capabilities reflect limited usage of Stages I and II, and Substages Ia and IIa of CFD development.

More advanced capabilities presently being sought by the user include extension of multielement analysis to complex three-dimensional configurations with large-scale flow separation, flows with strong vortex fields as produced by sharp leading edges and strakes, vortex peel-off due to merging boundary layers, and the coupling of elastic structures with nonsteady viscous flows.

Gap Between CFD Research and Usage

A new computational scheme and its testing by means of judiciously selected pioneering applications is only the first

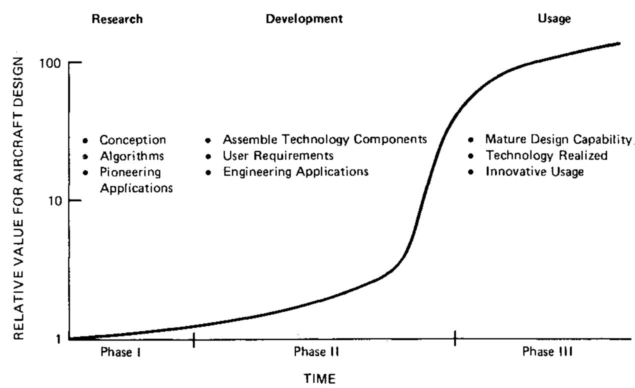

Fig. 7 Development cycle for a major computational capability.

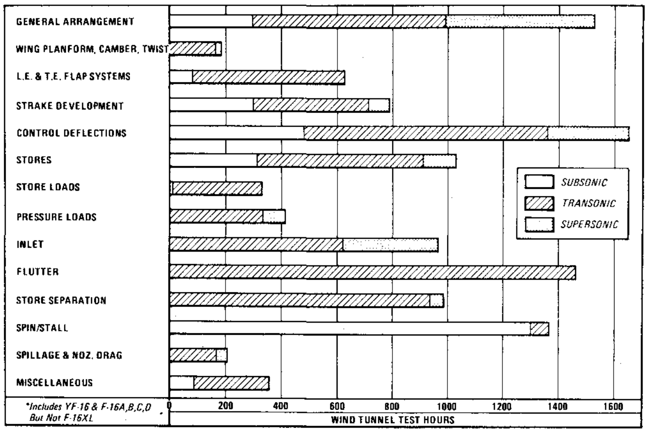

Fig. 8 F-16 wind tunnel test summary (1971-1982).

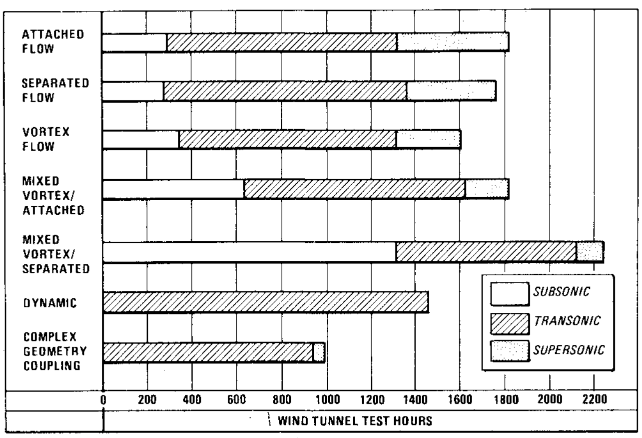

Fig. 9 Breakout of F-16 wind tunnel testing by flowfield complexity.

step in the long process of bringing it to a usable form for the airframe and engine designer.

After this first step, or research phase, has shown promise of success it is followed by two other major phases which are essentially development and usage phases as shown in Fig. 7.

The development phase involves production of a user-oriented method developed in such a way as to adequately address the engineering problems for which it was intended. It is generally a time-consuming and costly process which includes benchmark verification testing necessary to establish its readiness for use by the industry.

The usage phase is one in which the airframe and engine designers learn how to use the capability effectively. Numerous applications are investigated and refinements are introduced to the point where the CFD capability can result in a useful and valuable tool for the industry.

CFD and Test Facilities—Strengths and Weaknesses

CFD and ground test facilities play somewhat different roles and have different strengths and weaknesses. Both have inherent sources of inaccuracy. In CFD, even as Stage III computational capabilities evolve, the main source of inaccuracy is expected to be turbulence modeling.

Ground test facilities, on the other hand, are subject to flow disturbances and nonuniformities in the test area, and interference effects from walls, instrumentation, and model supports. Their Reynolds numbers are generally too low. However, as test facilities have been the primary source of design information since the early days of aviation, the aerospace community has learned to accept these deficiencies and apply corrections including correlations between wind tunnel and flight. Through long experience the designer has acquired a considerable degree of confidence in the validity of corrected aerodynamic data.

CFD as an emerging new technique for design verification requires a long trial period before a comparable degree of confidence in its use is achieved.

From the point of view of the information provided, CFD can, in principle, give considerably greater detail of a flowfield than is possible in any wind tunnel as all aerodynamic parameters are computed at each grid point. CFD provides a capability for configuration optimization or for determining the effect of configuration changes before commitment to model construction is made. In this respect, CFD helps in making more effective use of ground test facilities. On the other hand, when integrated forces and moments are desired, CFD is subject to the inherent mathematical inaccuracies associated with small differences of large numbers.

Ground test facilities, while limited in the degree of flow detail obtainable, provide a ready source of integrated flow information. Forces and moments are directly obtained by wind tunnel balance measurement. Also, when a vehicle configuration is firmed, a single wind tunnel model can effectively provide "data base" information—performance, stability and control, and airloads—for the various conditions of flight.

Types of Analysis in Aircraft Design

The requirements for design verification for aircraft and their engines are extensive and complex. As an example, the F-16, a modern fighter aircraft representing a high degree of aerodynamic technology, required the study of a large variety of configuration components and flowfield types. While it demanded more extensive analysis than a conventional cruise vehicle it does not have the added design complexities of a V/STOL capability with high-lift devices and vectored thrust.

Nearly 12,000 h of wind tunnel testing over the period from 1971 to 1982 were devoted to design verification of the F-16. A summary of the F-16 wind tunnel test program by configuration components and flight characteristics is given in Fig. 8. The breakdown of test hours into speed regimes—subsonic, transonic, and supersonic—illustrates the importance given to transonic performance as well as to spin, stall, and control characteristics at high angle of attack.

An attempt to relate wind tunnel test hours to flow regimes with increasing degree of complexity is shown in Fig. 9. It gives good insight into the capabilities sought in computational fluid dynamics as a method of aircraft design verification. The present development capabilities of CFD—Stage I and some extent of Stage II—are essentially limited to attached flow which represents only about 15% of the F-16 test program.

The anticipated availability of Stage III to compute the flowfield about a complete aircraft configuration in the next 15 years should extend by far the potential use of CFD for aircraft design verification. However, it will have to be subjected to extensive (and successful) testing for various practical configurations for the designer and management to accept its results with confidence.

Conclusions

In the next 15 years the capabilities of CFD as a tool for aircraft and engine design will increase tremendously and the unit cost of computation will drop by three orders of magnitude.

More effective use of ground test facilities will arise from computer- and CFD-enhanced operation although test costs are not likely to see a significant downward trend because of increased power and labor rates.

With the full-scale and high Reynolds number capabilities of the NASA Ames 80×120-ft facility and the Langley National Transonic Facility, and the capability for large engine testing of AEDC's Aeropropulsion Systems Test

Facility, ground test facilities and CFD should be adequate for design verification of aerospace systems with the possible exception of V/STOL aircraft.

The extent to which CFD comes into being as a method of design verification hinges on the confidence in its use by the aerospace designer and its acceptance by management from industry and government as a reliable, faster, and more economical means of systems development.

Designer confidence stems from extensive applications of CFD to specific design problems and assurance of accuracy by comparison of results with data from ground test facilities and/or flight tests.

From the management point of view, the resources at stake in the development of a new aerospace project are so enormous and performance guarantees so stringent that no significant departure from tried and proven methods of design verification are soon foreseen.

In the next 15 years, while the type of testing will change, no marked decrease in the use of ground test facilities is expected, but CFD will play an increasingly important role. CFD and ground test facilities will be used in a complementary rather than competitive mode and the end result will be a better product.

Acknowledgment

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