New regimes of flight become possible as supercomputers unlock the doors to their simulation and development.

The Electronic Wind Tunnel

BY JOHN RHEA

COMPUTATIONAL fluid dynamics—a technology that has emerged within the past decade because of the availability of ever more powerful supercomputers—is completely changing the way aerospace vehicles are developed.

This new technology represents as significant a milestone in flight as the invention of the wind tunnel, which it complements. Just as the wind tunnel was the essential first step toward heavier-than-air vehicles, the new computer-based analytical techniques will make possible the high-performance vehicles of the future.

The role of the wind tunnel is often overlooked. Everybody knows of the Wright brothers' success at Kitty Hawk, N. C., on December 17, 1903. What is not widely known is that three years earlier, back in their shop in Dayton, Ohio, the two bicycle-makers achieved the breakthrough that made that flight possible and ushered in the age of aviation. They built the first crude wind tunnel to test their designs before they flew them.

Until then there was only one way to test aircraft: Fly them. That's what all the other aviation pioneers did. Many of them, like Otto Lilienthal, died in the process. Others, like Samuel Langley, suffered a series of embarrassing failures.

The Wright brothers correctly guessed that the key to powered flight was the way the cross-section shape of the wings provided lift. Birds don't fly simply by flapping their wings; birds fly because their wings are remarkably efficient airfoils.

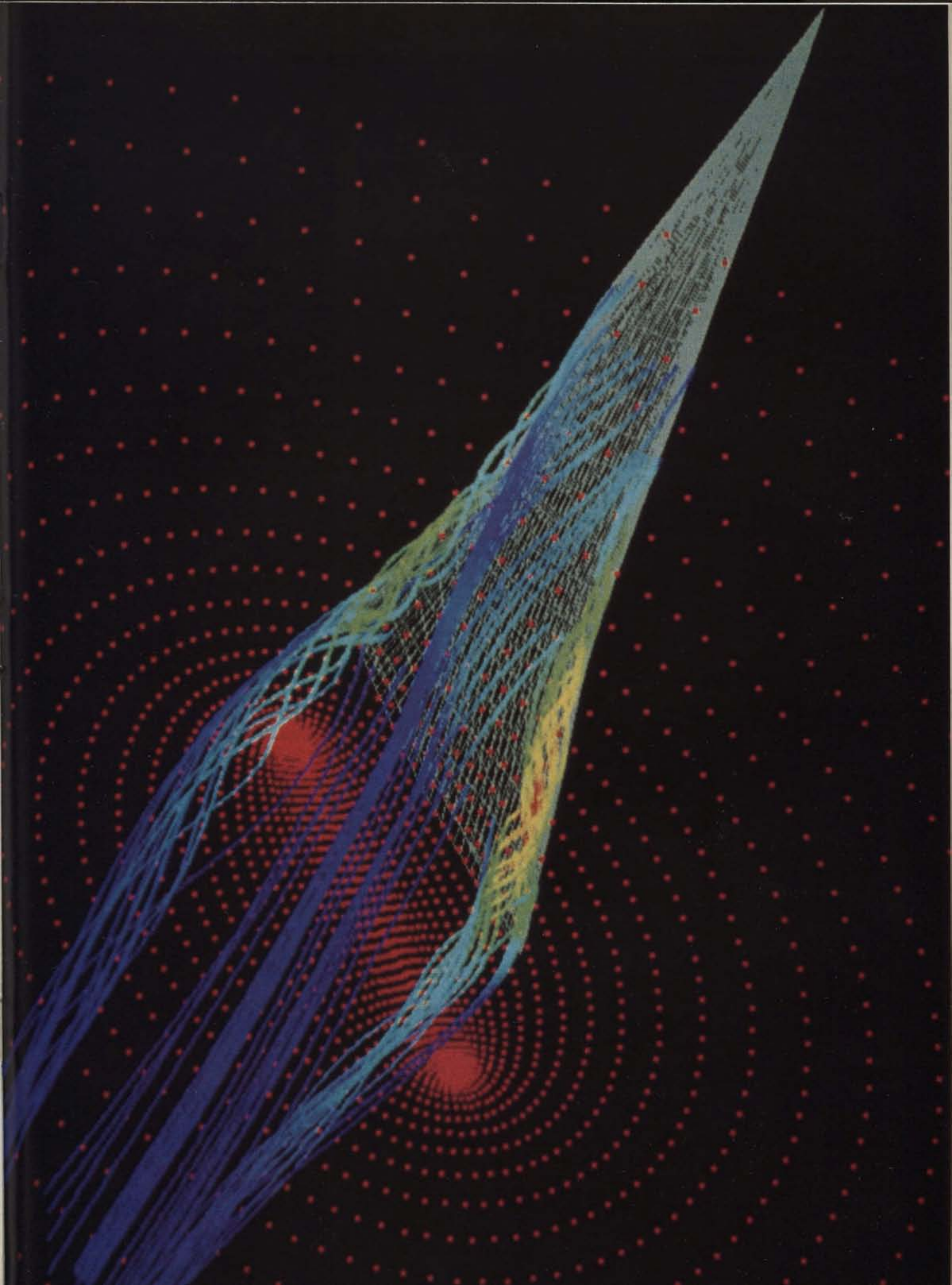
Once that principle of lift had been established in ground-based testing, the first flight was, scientifically speaking, almost an anticlimax. Nearly ninety years later, aircraft designers still base their work on this principle as they expand the flight envelope to ever greater speeds and altitudes.

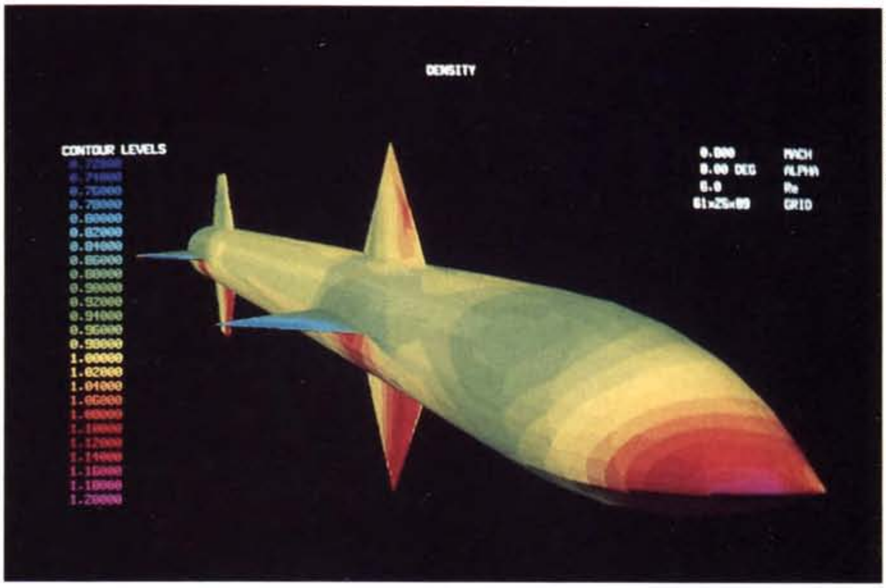
Testing the Next Generation

Air Force Systems Command operates the world's largest aerospace ground-test facility, the $3 billion complex of wind tunnels and environmental chambers at the Arnold Engineering Development Center (AEDC) near Tullahoma, Tenn. Since it opened for business

Flight conditions of an AMI-X test vehicle at Mach 0.8 with an eight degree angle of attack and six degrees of sideslip are simulated by a Cray X-MP, using McDonnell Douglas data. Using a graphics program developed by NASA's Ames Center, the computer then shows particle traces, colored by density (right), around the aircraft.

—Photo courtesy NASA Ames





—Photo courtesy NASA Ames

Given the same flight conditions simulated in the picture on the previous page, a Cray supercomputer calculates and displays the pressure contours around a generic missile. The pressure contours, varying with the changes of contour along the missile's surface, were calculated using BOD57 software, and the display was created using Ames Center's RIP graphics.

in 1951, this facility has tested most of the Air Force's new aircraft and missiles along with such NASA vehicles as Gemini, Apollo, and the Space Shuttle.

This also is where the Air Force will test its next generation of vehicles, including the Advanced Tactical Fighter and the X-30 National Aerospace Plane. These new vehicles will operate in a much more demanding environment and therefore will require much more complex testing. This is where computers become a critical factor.

Computerized simulation of aerodynamics is not new. The idea of "flying" an airplane in a computer before undertaking dangerous flight tests emerged after World War II from pioneering work by the Air Force, the National Advisory Committee for Aeronautics (NACA, the predecessor to NASA), and the aerospace industry.

What is new is the power of today's supercomputers, which can analyze the airflow around aerodynamic vehicles with sufficient precision to enable them to operate in the more demanding flight regimes of the future. Although the Wright brothers were the first to demonstrate ground testing, they made a fundamental error: They thought the flow of air *under* the wing provided the lift. Today aerodynamicists know that it is the partial vacuum created *above* the airfoil that is responsible for lift. An error like that was no problem for an aircraft with the performance of the Wright Flyer. It would be fatal for today's aircraft.

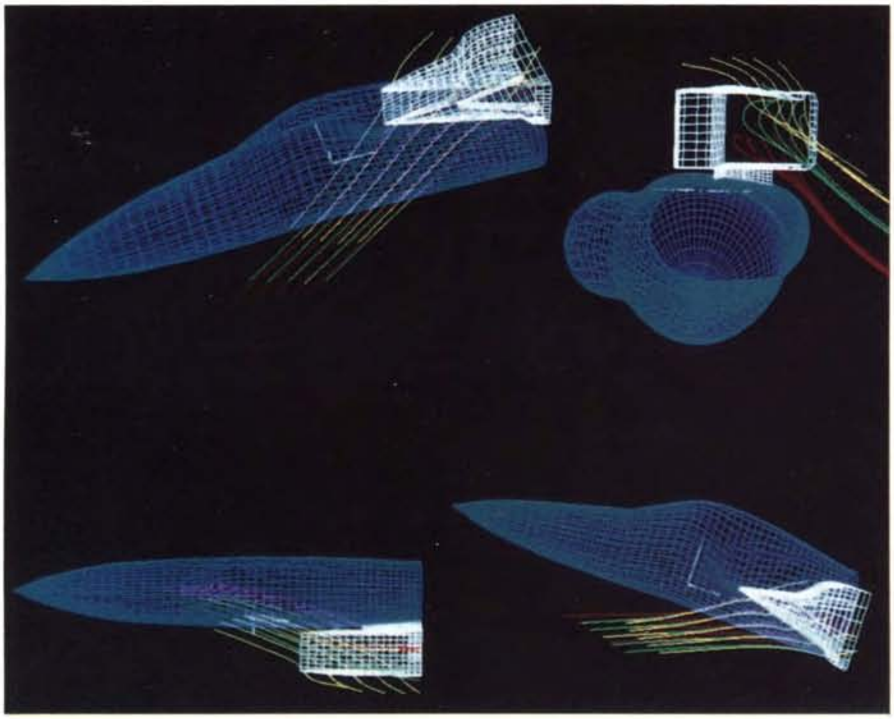
All new flight programs will rely on computational fluid dynamics. Breaking the term into its component parts makes it easier to understand. The *computational* part is obvious. This is a technology based on the use of computers to do calculations that were heretofore impossible. A *fluid* is what airplanes fly in; it's called air. The key to the concept is the third part—*dynamics*. By knowing the dynamic interaction of a vehicle with its environment, developers can optimize its performance.

Thus, CFD, as it's known, is essentially a set of software techniques that takes advantage of trends within the computer industry to build much more powerful machines for a variety of demanding applications.

At its Ames Research Center near San Francisco, for example, NASA has just put into operation a Cray Y-MP supercomputer capable of more than a billion computations a second. NASA is shooting for a trillion computations per second at its Numerical Aerodynamic Simulation Facility there by the end of the century.

New Tools at Tullahoma

At the Arnold test site, the Air Force operates two smaller Cray supercomputers, an X-MP and an earlier model Cray 1, both linked to each other and to a larger Cray 2 at Kirtland AFB, N. M. These are the



CFD prediction of the airflow around an F-15 forebody flying at Mach 0.6 with a thirty degree angle of attack and ten degrees of sideslip is shown from different angles with computed particle traces. Test engineers use the particle traces to determine what happens when airflow enters the engine inlet.

hardware tools of AEDC's CFD efforts.

The critical software tools have evolved over the past ten years, recalls Dr. Donald C. Daniel, chief scientist at the Arnold center. They consist of two parts: gridding, which is a mathematically generated picture of the air vehicle that he calls "a sophisticated checkerboard," and the algorithms that the computer uses to calculate the airflow over the simulated vehicle (or through it, in the case of a propulsion system). The more grid points that can be analyzed and the more sophisticated the algorithms (actually partial differential equations) used to analyze them, the more accurately the vehicle's performance can be calculated.

Furthermore, these calculations only begin on the vehicle's surface. They must be extended outward from the vehicle's body with emphasis on flow gradients (changes of flow) that affect vehicle performance. This would be a simple process if all aerospace vehicles were perfect spheres or cylinders. They aren't.

Because of the complex shapes that have to be tested, according to Dr. Daniel, the software engineers' task is to develop equally complex adaptive grids incorporating a feedback loop between the solution and the grid. This is a tedious process, and Dr. Daniel notes that it took a year to initially set up the grid and solve the flow field for the F-16 fighter.

Questions at Mach 15

Further complicating the process is the need for a better understanding of the basic aerodynamic processes. "We still don't understand turbulence," Dr. Daniel says. "It's more or less random, and we can't model a random event well." He expects there's enough research to be done in this area to keep scientists busy for the rest of this century.

The problem isn't so bad at subsonic and supersonic speeds. It's the transonic regime that worries scientists like Dr. Daniel. He calls that "the most nonlinear part" of the flight envelope, or the one in which the relationship between flow fields and vehicle performance is least understood. When it comes to hypersonic vehicles like the X-30 operating at Mach 15 at 300,000 feet, Dr. Daniel can only shrug, "What's your guess?"

Nonetheless, the basic principles of CFD are in place to handle future flight programs. Dr. Daniel pays tribute to Boeing for its pioneering work on its 757 and 767 commercial jetliners, adding that the Air Force will get maximum benefits from the technology on the ATF, "where the tools were there from the inception of the aircraft."

Dr. Edward M. Kraft, manager of the technology and analysis branch of the Calspan Corp. contractor team operating the wind tunnel test facilities at Arnold, describes the synergistic relationship among the three facets of vehicle testing: ground testing (in which the wind tunnel is the traditional tool), flight testing, and CFD. "Each tool has its limitations," he says, "but the other tools overlap and accommodate them."

This time-lapse photograph shows a laser-guided bomb separating from an F-15E in a wind tunnel. Such testing, in conjunction with CFD analysis, enables USAF to reduce actual flight testing by up to fifty percent.

Ground tests can't duplicate all conditions, particularly in the case of a spacecraft, but they are less costly and less dangerous. Flight tests are still essential because they represent the "truth," according to Dr. Kraft: "What you see is what you get." CFD is now entering the picture as part of an effort to do the diagnostics first and thus minimize ground testing and certification changes later in the program. As Dr. John H. Fox, a principal engineer with the Calspan technology and analysis branch, puts it, "We fly the aircraft on the computer."

"The name of the game is optimizing," adds Ralph E. Graham, chief of the aeronautical systems division at Arnold's directorate of aerospace flight dynamics test. "We're looking for the last one percent of performance."

Certifying Stores Release

Graham cites a very practical application of CFD that is paying off for the Air Force right now: certifying the release of stores. The Air Force has 110 kinds of stores (fuel tanks, bombs, missiles) in its inventory, he explains, and they're used with a variety of different aircraft. This adds up to thousands of possible combinations, so certifying a particular store for a particular aircraft can be a lengthy, costly process.

Instead, by using CFD in conjunction with wind tunnel test and analysis to determine the basic aerodynamic behavior of the stores and their host aircraft, the Air Force will be able to greatly reduce flight testing—in some cases by fifty percent—and "mix and match" the two. To do this entirely in a wind tunnel could take up to three years.

With CFD, wind tunnel testing and analysis, according to Graham, the process at AEDC can be cut to three months. How much money could this save? "The cost of an F-15," Graham quips. There's also a potential performance improvement in better circular error probable (CEP) for air-to-ground and air-to-air missiles.

Tracy Donegan, a Calspan senior engineer, describes a typical CFD project completed last August for the F-15 fighter: The entire aircraft (except its tail) with its seven pylons, a store, and pod was computa-

—USAF photo by Gary Barton

A computer at Wright-Patterson AFB, Ohio, displays Mach number contours on the surface of the F-15E Conformal Fuel Tank, attached LANTIRN pod, and GBU-12. The colors represent changing Mach numbers of the airflow as it follows the shapes of the stores. Cool colors represent low Mach numbers, and warmer colors represent higher Mach numbers.

tionally simulated with 1.1 million grid points. It took four engineers six months working part-time to develop all the algorithms for the grids and boundary conditions.

The initial purpose was to determine the aircraft/store flow field, but the program became much broader than that, Donegan explains. For the first time it gave the Air Force a picture of the flow field around a complete aircraft. That picture is available on demand at a video computer terminal in three dimensions and color-coded to show flow field gradients. This technology is now available to airframe prime contractors, and Donegan estimates the X-30 would require about the same number of grid points.

"CFD hasn't been extensively applied from cradle to grave," says Col. Dale F. Vosika, Arnold's deputy for operations, "but it does give us a level of expertise when integrated with ground and flight tests." In the case of the X-30, he notes, the lack of ground-test facilities will require a lot of computer simulation. This program, as well as the ATF, will require coordination with the Air Force's Aeronautical Systems Division (particularly the Flight Dynamics Laboratory) and the Air Force Flight Test Center. Colonel Vosika cites the complexity of the aircraft—higher performance, speeds, and maneuverability. The supercomputer complex at the NASA Ames Center will also be heavily involved in CFD studies to support the X-30.

Smarter Tests

John Rampy, technical director of operations at Arnold, praises CFD for enabling the Air Force to do what he calls smarter tests. "By understanding the external flow and the internal flow we can predict the baseline and reduce testing," he says. This leads to databases that are later updated with empirical data.

Reducing test time by using the electronic analog known as CFD has a major impact on costs, according to Rampy, who estimates that electrical power requirements eat up seventy percent of all test costs. That's cheaper than the operating costs of test aircraft, but it is still a cost to be avoided if possible.

In fact, this voracious appetite for electrical power is why the Arnold center is located in the heart of Tennessee Valley Authority territory. The availability of relatively low-cost power—plus water for cooling the test facilities—reduces overall costs.

They are still hefty. Col. (Brig. Gen. selectee) Stephen P. Condon, Arnold's Commander, has an electricity bill that would make most homeowners blanch: $2 million a month. That amounts to nearly 500,000 megawatt-hours a year—enough, he says, to provide power for a city of more than 50,000.

CFD Saves Money

Dr. Keith L. Kushman, chief of the center's facility technology division, has pinpointed some of the cost savings attributable to CFD. He figures the computational costs at Arnold at about $4 million a year, of which half is salaries and most of the rest is the amortized cost of the supercomputers. He has documented more than $2 million in cost savings to the center's customers (principally other elements of the Air Force Systems Command), but he estimates there is another $8 million in intangible savings from reduced risks to conventional ground-test equipment by doing the tests in a computer instead of wind tunnels. Furthermore, he maintains, half of the tests his team has conducted couldn't be done at all without CFD.

His colleagues at Wright-Patterson AFB, Ohio, agree. "Computational aerodynamic simulation now is a valid, inexpensive alternative to wind tunnel testing of new aircraft and aerospace designs," according to a statement by Dr. Joseph J. S. Shang, a technical manager at the Flight Dynamics Lab, after a series of simulations four years ago using the X-24C lifting body. The computed results duplicated the results of earlier wind tunnel tests for flow fields and aerodynamic forces on the vintage 1974 experimental reentry vehicle.

As supercomputers become even more powerful, the technology of CFD can be extended even further, according to Arnold chief scientist Dr. Daniel. He is more concerned about memory capacity than about multibillion-operation speeds and says even the 256-million-word memory of the top-of-the-line Cray 2 "won't be nearly enough" for some of the projects he has in mind.

"The great thing about supercomputers is that they unlock the mind," Dr. Daniel concludes. ■

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