88-1997

THE BASIC AERODYNAMICS RESEARCH TUNNEL – A FACILITY DEDICATED TO CODE VALIDATION

William L. Sellers III*, Scott O. Kjelgaard**
Analytical Methods Branch
NASA Langley Research Center
Hampton, VA

Abstract

Computational fluid dynamics code validation requirements are discussed together with the need for close interaction between experiment and code development. Code validation experiments require a great deal of data and for the experiments to be successful, a highly-productive research facility is required. A description is provided of the NASA Langley Basic Aerodynamics Research Tunnel (BART); especially the instrumentation and experimental techniques that make the facility idealy suited to code validation experiments. Results are presented from recent tests which illustrate the techniques used in BART.

Introduction

Computational fluid dynamics (**CFD**) methods are playing an ever increasing role in the design of aircraft and are progressing toward the prediction of the three-dimensional flowfield about complex geometries at high angles-of-attack. These methods usually involve solutions of the Euler or Navier-Stokes equations and typically require assumptions about the structure of the flowfield to make the solution more tractable.

Detailed experimental flowfield and surface measurements, with minimal, quantifiable errors, are required to validate these methods. To date, few sets of experimental data exist which are of sufficient detail and completeness to allow a definitive validation of current computational methods. The flowfields of interest are usually complex, and difficult to measure, and therefore require state-of-the-art instrumentation. The large volume of experimental data places demands on a facility. These demands are met with highly-automated data acquisition and control systems and large amounts of mass storage to maintain the data base.

The future progress of CFD methods will depend on their ability to accurately model the fundamental physics of the flow. This ability can only be assessed by comparisons between detailed experimental and computational results. These experiments will require a close interaction between the code developer and the experimentalist. This interaction helps to design experiments that are productive, by focussing on specific items of interest.

This paper will describe the NASA Langley Basic Aerodynamics Research Tunnel (**BART**) which is a facility dedicated to obtaining the detailed flowfield data required for code validation. The instrumentation systems and techniques that make the tunnel a highly productive research tool for code development and validation will be described and typical comparisons between the experimental data and computational results will be presented. Many of the features that make the facility suitable for code validation experiments also enable the tunnel to undertake detailed flowfield studies over complex aircraft configurations. Flowfield surveys from recent high-alpha investigations of fighter configurations will also be used to demonstrate some of the capabilities of the facility.

Nomenclature

L	centerline length of 75° delta wing model (22.392 inches)
R_n	Reynolds number, $V_\infty L/\nu$
P	pitot or reduced total pressure, psf
q	dynamic pressure, $\frac{1}{2}\rho V_\infty^2$
St	stokes number
V_∞	freestream velocity, ft/sec
u, v, w	velocity components in the body axis system, ft/sec
x, y, z	cartesian coordinates in the body axis system
α	pitch angle measured by 5-hole probe, deg
β	yaw angle measured by 5-hole probe, deg
ν	kinematic viscosity, ft^2/sec

* Research Scientist, Analytical Methods Branch, Senior Member AIAA
** Research Scientist, Analytical Methods Branch

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ρ	density, slug/ft^3
θ	total flow angle, $\sin^{-1}(\frac{\sqrt{v^2+w^2}}{\sqrt{u^2+v^2+w^2}})$
ω	vorticity, $\frac{L}{V_\infty}(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x})$
Subscripts:	
p	particle
t	transition
∞	at freestream conditions
Superscripts:	
~	Root Mean Square (RMS)

Code Validation Requirements

With the advent of the new generation supercomputers with large memory capacity, and improvements in algorithms and grid generation, the CFD codes are progressing toward the calculation of complex flowfields where little experimental data presently exists or is not technically feasible to acquire. One of the goals of a 1980 Stanford Conference On Complex Turbulent Shear Flows[1] was to reach a consensus on trustworthy data sets that could be used for flow modeling or for checking the results from computer codes. During the conference, a position paper[2] was presented which discussed the experimental data requirements for CFD. Different type of experiments were classified and the experimental requirements for each category discussed. Several of the many valuable comments and recommendations which were provided for future experiments are reiterated below.

One important recommendation was that future experiments must be well documented, with a statement of the experimental uncertainties. The understanding of the uncertainties must have a central role in the code validation effort because it is important (1) to the comparison of data from different test facilities or techniques, (2) to the comparison of data to computations from different algorithms, and (3) to determining whether data sets should be accepted or rejected for code validation.

It was also suggested that experiments should be conducted in more than one laboratory or facility, because redundant testing helps uncover or isolate problems generated by the experimental techniques or facilities. This recommendation becomes even more important in cases where the flowfields being measured are sensitive to the input turbulence spectrum. In addition, the experimenter should record the time-dependent or fluctuating signals so that data can be re-analyzed in later years for different quantities of interest or if questions arise about the data set.

The NASA Aerodynamics Advisory Committee (**AAC**) formed an Ad Hoc Committee for Code Validation in 1986. The goal of the committee was to provide a critical review of the NASA's efforts in code validation. In July of 1987, the first NASA CFD Validation Workshop[3] was held. During the workshop the committee's recommendations were summarized and comments were solicited from the industry, university and government representatives that were present.

The committee's review reiterated the need for close interaction between the code developer and the experimentalist. The committee developed specific definitions from which experiments would be classified and what was required for code validation. Validation was defined as "*detailed surface-and-flow-field comparisons with experimental data to verify the code's ability to* **accurately model** *the* **critical physics** *of the flow*". It was further stated that, "*validation can occur only when the accuracy and limitations of the experimental data are known and thoroughly understood and when the accuracy and limitations of the code's numerical algorithms, grid-density effects, and physical basis are equally known ...*".

Several of the committee's recommendations are repeated below. The committee concluded that CFD validation is severely hampered by the lack of critical measurements under realistic conditions. In addition, measurements must be taken with adequate accuracy and resolution, and with redundant instrumentation, in order to evaluate the capability of CFD methods to predict details and to explore the boundaries of application for specific codes. The committee also recommended that specific instrumentation and facilities need to be developed when the state-of-the-art is inadequate.

Basic Aerodynamics Research Tunnel

With the guidelines provided by the 1980 Stanford conference, the Analytical Methods Branch (**AMB**) of the NASA Langley Research Center set out to develop a facility dedicated to code validation and incorporate as many of the recommendations as possible into the tunnel operations and data acquisition. A commercially available wind tunnel was acquired in November 1984, with certain features such as the honeycomb cell size, screen mesh and porosity specified by the AMB. An important design specification for the tunnel was that it must be simple to operate and maintain.

Wind Tunnel

The Basic Aerodynamics Research Tunnel shown in figure 1 is an open-return wind tunnel with a test section 28 inches high, 40 inches wide and 10 feet long. The test section is divided into 2-five foot long bays. The

maximum flow velocity in the test section is 220 ft/sec which yields a R_n/ft of 1.4 million. The airflow entering the test section is conditioned by a honeycomb, four anti-turbulence screens and an 11:1 contraction ratio. The four-inch thick honeycomb has a 0.25 inch cell size. The screens are 20 mesh per inch with a porosity (ratio of open area to total area) of 64%. The tunnel is powered by a 125 horsepower AC motor coupled to a magnetic clutch. An electronic speed controller maintains the fan rpm within .1% of full scale (less than 1 rpm variation).

These flow conditioners, coupled with an excellent fan speed controller, provide a low-turbulence, uniform flow in the test section. The variation in the longitudinal component of turbulence intensity with test section q is presented in figure 2 and shows that the u-component of the turbulence intensity ranges from approximately .05% at $q = 10$ lb/ft^2 ($V_\infty = 92$ ft/sec) to .08% at $q = 45$ lb/ft^2 ($V_\infty = 195$ ft/sec).

Optical access to the test section is critical in code validation experiments, not only for flow visualization, but for non-intrusive instrumentation such as the laser doppler velocimeter (**LDV**). The plexiglass windows in the walls and ceiling were made as large as structurally possible and can be replaced with 11 mm thick glass for tests involving the LDV system.

Data Acquisition and Control System

Code validation requires large amounts of experimental data. A highly integrated and automated data acquisition and control system (DACS) is required to acquire and reduce this data in a timely fashion. Real-time color graphic displays of flowfield parameters are required to ensure that the experiment is progressing properly and to assimilate the large amount of information that is acquired.

A schematic of the BART DACS is shown in figure 3. The DACS is an integration of two different computer systems. The Tunnel Data Acquisition and Control (TDAC) computer system is used to acquire low transfer rate data from the tunnel and several peripheral systems. This desktop computer system has a Motorola 68000 based CPU with 4 Megabytes of memory. A computer-controlled 3-component hot-wire system and an electronic scanning pressure system have an interface with the TDAC, which has software that automatically checks each system and re-calibrates them for changes such as temperature drifts. The TDAC also drives a 2-axis traverse system which is used for pressure probe surveys or for the LDV seeding system. The TDAC also provides the real-time color graphic display of the flowfield parameters to monitor the progress of the test.

A larger minicomputer handles the on-line acquisition and reduction of the LDV data, movement of the LDV traverse system and post-processing of the flowfield data. The minicomputer will be linked to the computational fluid dynamics lab to enable efficient transfer of data for comparison with the computational results. The system is fully automated and many of the flowfield surveys are done under complete computer control.

Marvin[4] recently discussed the role of experiment in the development of CFD methods. The pacing items for both the computational and experimental efforts were discussed and he also described the requirements for future wind tunnels used to verify CFD methods. The BART tunnel and its instrumentation and data systems just described meet the requirement of an idealized system as described by Marvin in reference 4.

Experimental Techniques and Instrumentation

The test philosophy adopted for use in BART was again guided by the recommendations of the 1980 Stanford Conference[2] in that; "*...it is better to do one experiment with extreme thoroughness, including redundant measurements with more than one type of instrument, than to provide a variety of experiments...*". Therefore, only a few experiments that were selected with the guidance of the code developers, are scheduled for testing in the BART tunnel. Redundant measurement techniques are used to provide cross-checks on the accuracy of the various instrumentation systems.

The following sections describe the experimental techniques and instrumentation that are used in a typical test. The examples that are provided come from a recent test of a 75° delta wing[5,6] along with selected results from tests involving fighter configurations at high angles of attack. The 75° delta wing experiment is typical of a code validation experiment in BART. The test consisted of several phases, each one utilizing a different measurement system to provide cross checks on accuracy. The test was conducted at one angle of attack and results include surface flow visualization, off-body flow visualization, and detailed flowfield surveys for various Reynolds numbers. Flowfield surveys were obtained using three different techniques at several longitudinal stations with as many as 3300 data points at each station.

The computational results presented in this paper were obtained utilizing the CFL3D code[7], which uses a thin-layer formulation of the Navier-Stokes equations. The nonlinear method uses second-order accurate upwind-biased spatial differencing and linearized, backward time differencing. A full approximation scheme multigrid algorithm is used to accelerate convergence to the steady state.

Flow Visualization

Flow visualizations from a variety of techniques are

used routinely in the facility. The particular method chosen depends on the information that is desired. At the very simplest, flow visualization is used to provide a quick look at the overall characteristics of the flowfield. In other cases, flow visualization provides quantitative data for certain physical aspects of the flow for comparison with other instruments or calculations.

Surface flow visualization is used primarily to determine the position of separation lines on the model surface and to examine the effect of Reynolds number on the location of transition. A titanium dioxide (TiO_2) technique[5] has been used extensively in BART. Surface flow patterns are obtained using a mixture of TiO_2 and kerosene with a small amount of oleic acid added as an anti-coagulant. After the mixture is painted on the surface of the model, the airspeed in the test section is brought up to the test condition. The kerosene evaporates and leaves the TiO_2 deposited on the surface. The evaporation rate can be slowed down by substituting mineral or baby oil for the kerosene.

The TiO_2 technique provides the fine-grain detail that is necessary to identify features such as boundary layer separation and attachment lines on the surface of the model. Figures 4a and 4b show the experimental and computational surface flow streamlines(from reference 6) generated by a 75° delta wing at 20.5° angle of attack at a Reynolds number of 0.5 million. The computational surface streamlines were calculated using the grid points closest to the surface and integrating particle paths using ±time. The line closest to the leading-edge is an attachment line, not the tertiary separation line seen in the experiment. The semispan location of both the secondary and tertiary separation lines are predicted within 1% by the computational code.

The location where the boundary layer undergoes transition from laminar to turbulent is important for validating computational methods, especially Reynolds-Averaged Navier-Stokes codes which use turbulence models. Sublimating chemicals and other techniques can be used to determine the point where the boundary layer undergoes transition. For delta wing configurations the TiO_2 will also identify the transition point because the secondary separation line will sweep further outboard toward the wing tip when transition occurs. During a test of the 75° delta wing[5] the transition location was documented for Reynolds numbers between 0.5 and 2.0 million in increments of 250,000. The transition Reynolds number,

$$R_{n_t} = x_t V_\infty / \nu$$

where x_t is the streamwise distance from the apex to where transition begins, ranged from 800,000 to 900,000. The boundary layer transitions at the trailing edge of the wing at a Reynolds number of approximately 1.0 million and the transition point moves forward to $x/L \approx 0.4$ at a Reynolds number of 2.0 million.

A scanning laser light sheet is used to obtain a rapid global look at the flowfield and to determine areas of interest for later detailed investigation. The system is also used to determine if there are probe interference effects on the flowfield. Smoke is introduced into the flow upstream of the honeycomb, and is illuminated with a thin sheet of laser light to provide a cross-sectional view of the flowfield. The smoke is produced by vaporizing propylene glycol at a temperature of 380° F. The light sheet is generated using an argon-ion laser as the light source with a twin-mirrored galvanometer laser-light-sheet generator. The system was designed by Rhodes[8], et. al. at NASA Langley. The system can be used in a variety of modes and provides either single or simultaneous multiple light sheets. In addition, the system can rotate the sheets through 360° or provide a single scanning sheet with adjustable scan rates. Figure 5 shows a photograph of a typical laser light sheet flow visualization over an advanced fighter configuration and illustrates the capability of the system to produce simultaneous multiple light sheets.

Pitot Pressure Surveys

Pitot pressure measurements are probably the simplest flowfield measurements to make. The probe most commonly used in the BART is a boundary-layer probe approximately .024 inches wide by .013 inches high with a wall thickness of .005 inches. The pitot probe was chosen because its small size enables measurements to be made with high spatial resolution. However, when a probe is introduced into a complex flowfield, the effect of the probe on the flowfield as well as the probe's own measuring characteristics must be examined. It was recognized that this probe would not be capable of measuring the true total pressure since the probe is not always aligned in the direction of the local velocity vector; hence it is referred to as **pitot** pressure and not total pressure. The probe was however, carefully calibrated to document[6] its sensitivity to flow angle and techniques have been developed which enable the computational codes to account for the characteristics of the probe when comparing with experiment.

A computer-controlled probe-positioning system is used to traverse the probe through the flowfield. At the beginning of each survey and after the airspeed is brought to the test condition, the model surface is located through the use of an electrical probe fouling circuit. This is done to lessen the uncertainty in measurement location due to the effect of the probe and model deflections under aerodynamic loading. Once the model surface is located, the flowfield survey is conducted under complete computer control.

Pressure data is measured using an electronic scanning pressure system with 1 psid transducers. The accuracy of these transducers is ±.001 psi. This accuracy is a function of temperature (±.0005 psi/° F); therefore, the data acquisition system continuously monitors the freestream temperature and automatically performs a recalibration when the temperature changes more than 2° F. After stepping to each measurement location and pausing 0.5 seconds, the mean pressure is determined by averaging 255 samples acquired over a 1 second time interval. The pressure transducers are referenced to the total pressure downstream of the last anti-turbulence screen and therefore, measure the pitot pressure deficit from that location. Real-time color graphic displays of the pitot pressure flowfield are produced to ensure there are no lead/lag pressure errors induced by the movement of the probe through the flowfield.

Pitot pressure surveys for the 75° delta wing at 20.5° angle of attack are shown in figure 6. Each survey station contains approximately 2,800 measurement points and took approximately 2 hours to acquire. The data acquisition software has the option of specifying an "embedded grid" in the flowfield just acquired. In a recent test for example, the region enclosing the secondary vortex was chosen for the embedded grid. The data acquisition system automatically surveys the specified region with a user-selectable grid size. The embedded grids for the secondary vortex typically contained approximately 1700 data points.

The flowfield over a complex aircraft configuration represents a much more difficult survey task than a flat delta wing due to the irregular surface. The data acquisition software handles this situation by generating a body-fitted grid. The first task is to "digitize" the surface of the model at specified span stations with the probe and the fouling circuit. The DACS stores the model surface or "base-survey line" in memory and creates a survey grid by stepping a constant vertical increment from the previous survey line. An example of this technique is shown in figure 7, which shows the pitot pressures measured over an F-18 model at 23° angle of attack. Digitizing the surface of the model takes approximately one hour and represents a significant portion of the survey time at a cross section. In this test, the grid size changed from station to station. The first survey plane near the front of the leading edge extension (LEX) contains approximately 2,800 measurement locations and took approximately 2 hours to acquire. The last survey station just ahead of the twin-tails contains approximately 5,800 measurement locations and took approximately 8 hours to acquire (3 hours for surface digitization).

5-Hole Probe Surveys

A hemispherical tipped, 0.125 inch diameter, 5-hole pressure probe is used to measure the yaw angle, pitch angle, and total velocity in the flowfield. The probe is calibrated using equations derived from the potential flow about a sphere. The derivation of the calibration equations and the method of acquiring the calibration data are described in reference 9. The error in α, β, and q deduced from the 5-hole probe calibration data are presented in figures 8a, 8b, and 8c. The 5-hole probe acquires data using the same probe positioning system and pressure measurement technique described above. However, due to the relatively large size of the 5-hole probe, the embedded survey grid option was not used to measure the secondary vortex. The real-time color graphic display presents the crossflow velocity vectors with the color of the vector representing the longitudinal or streamwise component of velocity.

Results from a typical 5-hole probe survey over a 75° delta wing are shown in figure 9. The data was obtained at x/L=0.7 at a Reynolds number of 0.5 million. This figure clearly shows the amount of detail that was obtained in the experimental effort. A typical survey plane contained approximately 3,300 measurement locations and took approximately 3 hours to acquire. The figure compares the measured cross flow velocity vectors with the results from the CFL3D Navier-Stokes code[7]. The figure shows the relative locations where the data was acquired experimentally and predicted computationally. The vectors show that the computational grid is clustered near the surface to better resolve the viscous effects in the boundary layer. The experimental grid is a cartesian-type which places equal emphasis on the entire flowfield. The figure also shows that the experimental survey grid has a spacing finer than the computation in the region above the primary vortex core. A comparison between the experimental and computational vorticity calculated from the velocity field at x/L=0.9 is shown in figure 10. The computation predicts the general trends of the flowfield. The vortex strength in the primary vortex is underestimated by the code. A grid refinement study has shown that the computational grid needs to be denser in the region of the primary vortex to model accurately the strong gradients near the core. The computational method is presently being modified to provide an embedded grid in the region of the primary vortex core.

3-Component Laser Doppler Velocimeter Surveys

Many of the flowfields that are of interest for code validation experiments are complex and difficult to measure and therefore, require state-of-the-art instrumentation. The LDV is capable of obtaining accurate velocity measurements in flowfields with reverse flows, large shear gradients and velocity fluctuations.

BART is equipped with a dedicated, 3-component LDV system to enable the nonintrusive measurement of the flowfield. The LDV system is an orthogonal crossed-fringe configuration with the receive optics mounted 90° off-axis. The 514.5, 496.5 and 476.5 nanometer wavelengths are used to measure the lateral (v), streamwise (u), and vertical (w) velocity components, respectively. Bragg cells are used to provide directional measurement capability in all three velocity components. The sample volume is spherical in shape and has been calculated to be approximately 150-μm in diameter. A photograph of the laser beams crossing over the 75° swept delta wing model is shown in figure 11.

The optics and laser move as a unit on a traversing system that provides 1 meter of travel, with 10-μm resolution, in all three axes. The design of the traverse system provides flexibility in optical mounting and allows the optics to be remounted in forward scatter or 180° back scatter configuration should the test require. The traverse system is shown installed around the tunnel test section in figure 12. A detailed description of the LDV system which includes its design and operation, is presented by Meyers and Hepner in reference 10.

The flowfield is seeded with 0.8-μm polystyrene latex microspheres which are fabricated at NASA Langley using the technique described by Nichols[11]. The seed particles are suspended in a mixture of alcohol and water and are injected into the flow upstream of the honeycomb using an atomizing spray nozzle. The spray nozzle is mounted on a computer-controlled 2-axis traverse system which allows remote positioning of the spray nozzle. Typically several hundred to 4096 velocity samples are obtained at each measurement location in the flowfield. The actual number of samples and the acquisition rate depends on the particular location in the flowfield and the particle seeding rate.

The ability of a particle to track the streamlines in the flowfield, and thus the accuracy of the LDV, is related to the size of the particle. Theoretical predictions of particle trajectories in swirling flows were reported by Dring and Suo[12]. They concluded that the particle trajectory in a free vortex swirling flow is governed primarily by the Stokes number (St) and when the Stokes number is less than 0.01, the particle will follow the circular streamlines of the free vortex. The 0.8-μm particles used in BART have a density $\rho_p = 2.03727$ slugs/ft^3. The Stokes number for these particles, based on the radius and the swirl velocity at the edge of the vortex core, is 0.007. The numerical procedure described by Dring was used to predict the particle trajectories for a free vortex with swirl velocities based on values measured during the 75° flowfield investigation[6]. The predictions show that the particles used during this test will follow the streamlines of the vortex with an accuracy better than 1%.

The LDV system has been used to provide redundant flow angle and velocity measurements for direct comparison with the 5-hole probe. This data helps to assess the measurement errors caused by introducing the probe into a vortical flowfield. LDV velocity surveys of the flowfield above the 75° delta wing were conducted at selected chordwise stations and at the same measurement locations that were obtained with the 5-hole probe. Figure 13 shows a comparison between the cross-flow velocity vectors that were obtained using the LDV and the 5-hole probe at x/L=0.9 for a Reynolds number of 1.0 million. The per cent differences between the measured velocity components are presented in figure 14 and were calculated assuming that the LDV measurements were the reference. The equation used to calculate the u-component error is shown below:

$$u_{error} = 100 * \frac{(u_{LDV} - u_{5-hole})}{\sqrt{u_{LDV}^2 + v_{LDV}^2 + w_{LDV}^2}}$$

The figure shows that in regions where the velocity gradients are low, the 5-hole probe does a reasonable job of measuring the flowfield quantities (probe error is less than 5%). However, the 5-hole probe has errors ranging from 17% to 35% in the core of the vortex.

The LDV system has the ability to measure velocities very close to the surface of the model for simple configurations. Figure 15 shows the boundary layer that was measured near the centerline of the 75° delta wing at x/L=0.9 for a Reynolds number of 0.5 million. The data show that the boundary layer was laminar and was approximately 800-μm thick. The LDV was able to measure all three velocity components in the boundary layer within 250-μm of the surface and was able to provide a good definition of the profile.

The LDV system has also been used to measure the velocities in flowfields that contain burst vortices. When a vortex bursts, the axial velocity at the core of the vortex abruptly stagnates followed by a rapid expansion of the core. After the expansion the flow changes to a highly-turbulent swirling state. Vortices can burst asymmetrically and induce substantial rolling moments. Figure 16 shows a flowfield survey over the 75° delta wing at an angle of attack of 40° . The data were obtained at an x/L=0.7 for a Reynolds number of 1 million. The figure shows that the vortices have burst asymmetrically. The axial velocity in the core of the vortex on the left contains a small region of reverse flow (figure 16a). The vortex on the right shows a retardation of the axial velocity in the core and little or no reverse flow.

Concluding Remarks

Computational methods are playing an ever increasing role in the design of aircraft and are progressing toward the prediction of the three-dimensional flowfield about complex geometries at high angles-of-attack. Detailed experimental flowfield measurements are required to validate these methods and ensure that the codes are accurately modeling the physics of the fluid flow. With the guidelines provided by the 1980 Stanford conference, the Analytical Methods Branch of the NASA Langley Research Center set out to develop a facility dedicated to code validation and incorporate as many of the recommendations as possible into the tunnel operations and data acquisition. The Basic Aerodynamics Research Tunnel was acquired in November 1984 and dedicated to obtaining the highly-detailed flowfield data required for code validation. The facility has been equipped with state-of-the-art instrumentation and data reduction computers.

Code validation experiments conducted in BART require a close interaction between the computational code developers and the experimentalists. This interaction is required so that experiments are designed to address the specific needs of the computational method. These experiments typically have the following requirements:

1. large quantities of highly-detailed flowfield data
2. state-of-the-art instrumentation systems
3. statement of measurement errors or uncertainty
4. redundant measurements using different instrumentation techniques

The characteristics of BART meet these requirements. These characteristics also make the facility ideally suited for flowfield studies over complex aircraft configurations.

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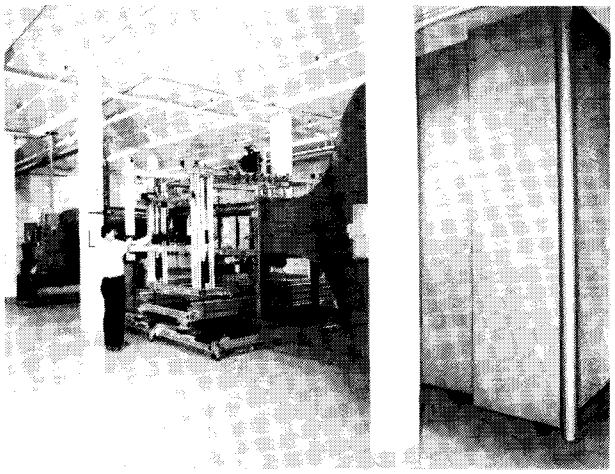


Figure 1. Photograph of the Basic Aerodynamics Research Tunnel

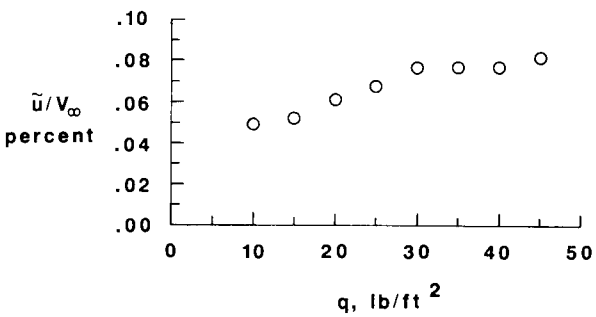


Figure 2. Variation in longitudinal turbulence intensity with q.

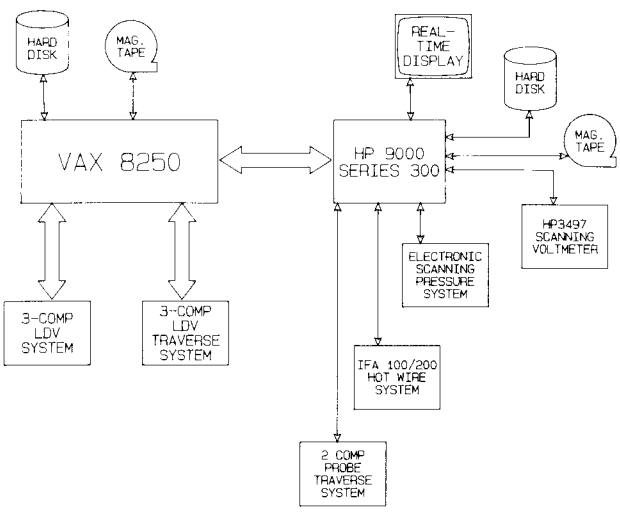
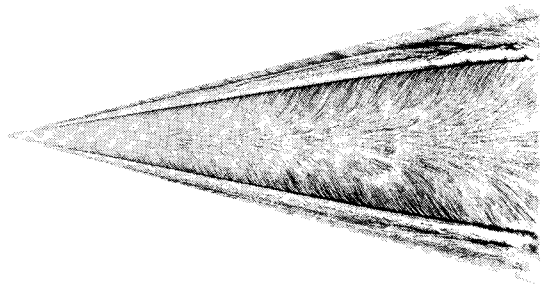
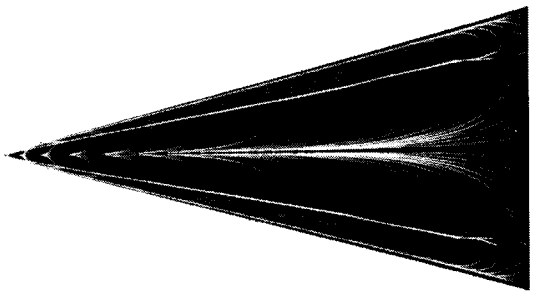


Figure 3. Schematic of the BART Data Acquisition System.



a). Experiment



b). Computation

Figure 4. Surface flow visualization over 75° delta wing; α =20.5° , $R_n = 0.5x10^6$

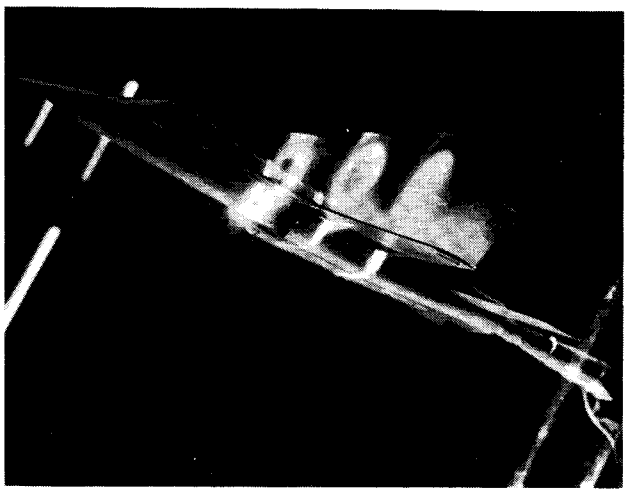
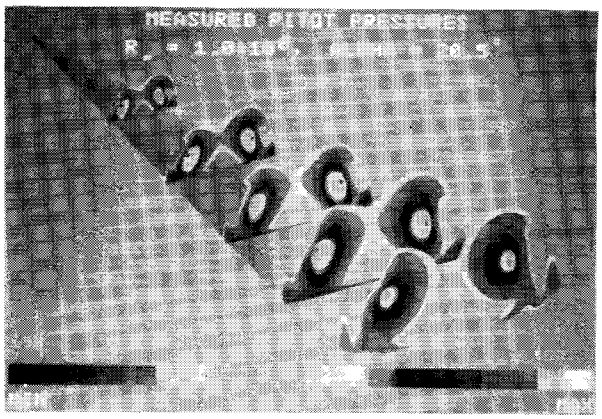
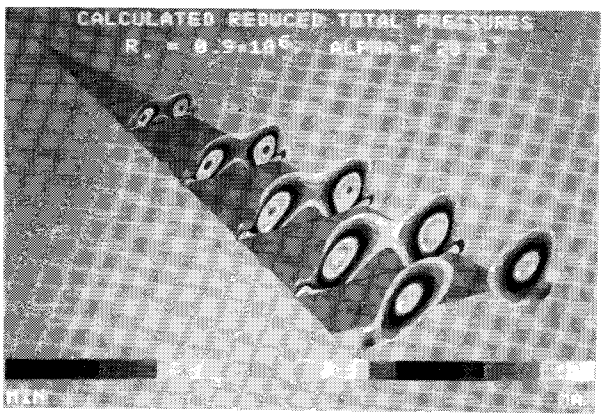


Figure 5. Photograph of laser light sheet flow visualization over F-17; α = 25° , R_n = 326,000



a). Experiment



b). Computation

Figure 6. Pitot pressure contours over 75° delta wing; α =20.5° , $R_n = 1.0x10^6$

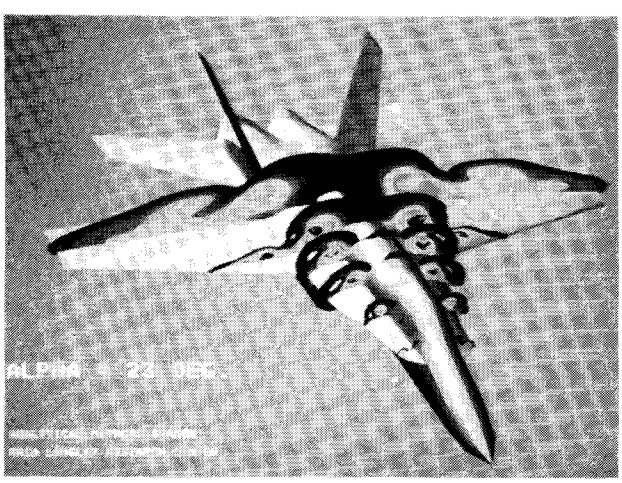
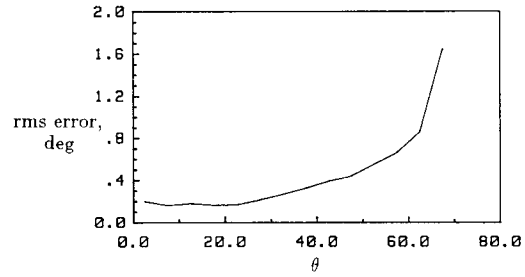
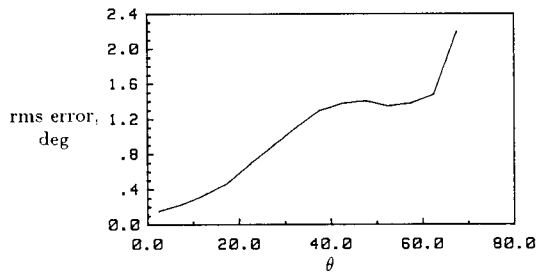


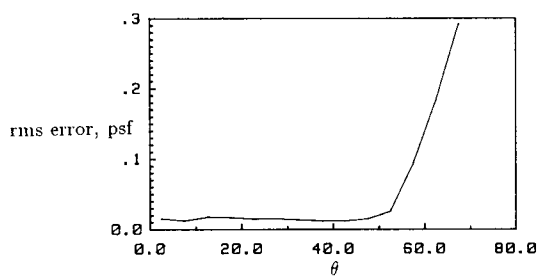
Figure 7. Pitot pressure contours over F-18; α =23.0° , $R_n = 346,000$



a). Error in α versus total flow angle.

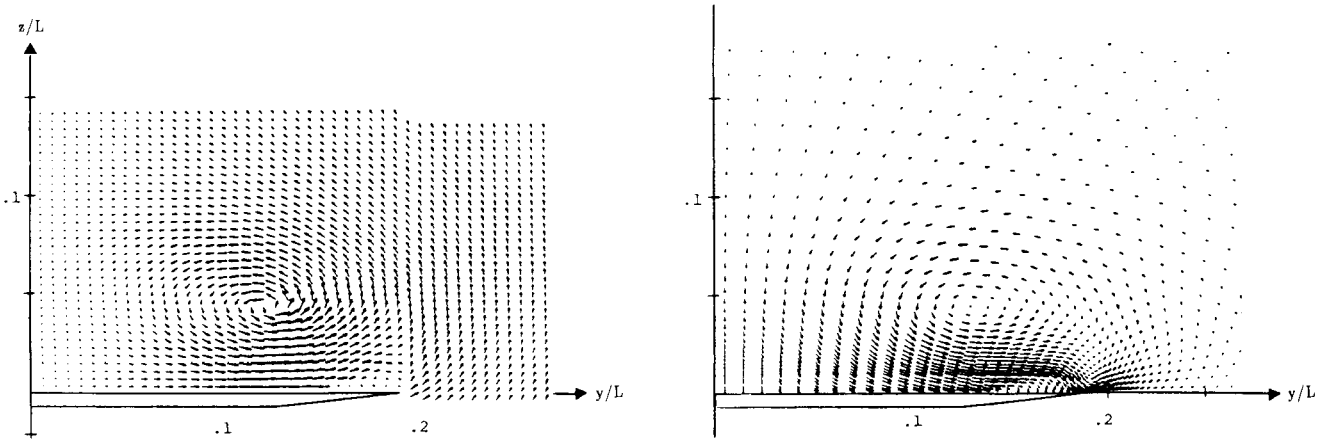


b). Error in β versus total flow angle.



c). Error in q versus total flow angle.

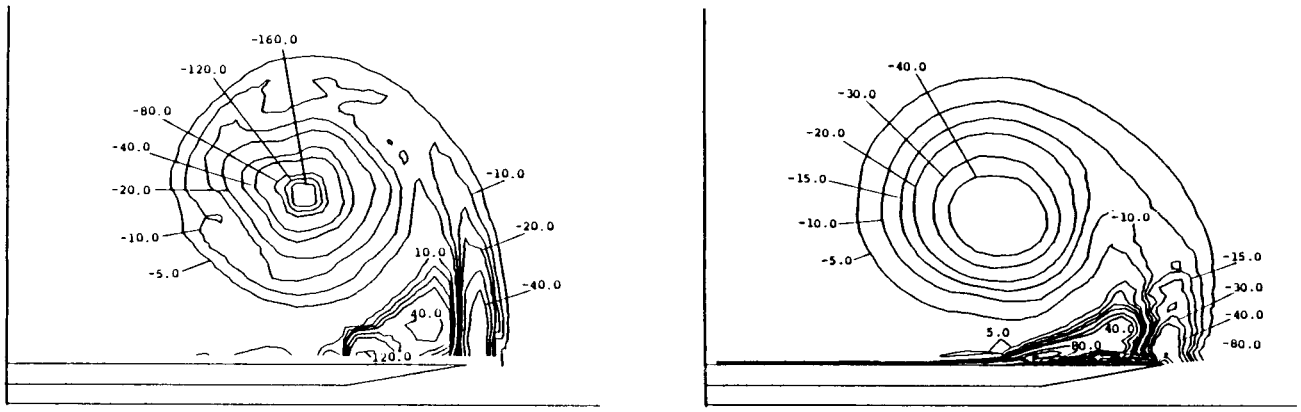
Figure 8. Characteristics of the 5-hole probe used in BART.



a). Experiment

b). Computation

Figure 9. Cross flow velocity vectors over 75° delta wing; α =20.5° , R_n = 0.5x10^6, x/L=0.7.



a). Experiment

b). Computation

Figure 10. Vorticity Contours over 75° delta wing; α =20.5° , R_n = 0.5x10^6, x/L=0.9

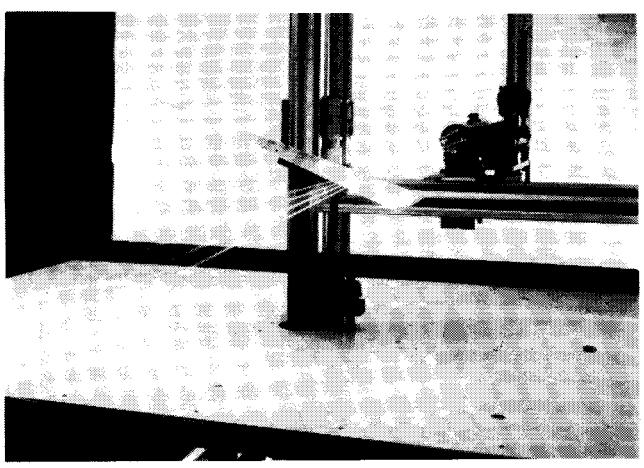


Figure 11. Photograph of the 3-component LDV system in operation.

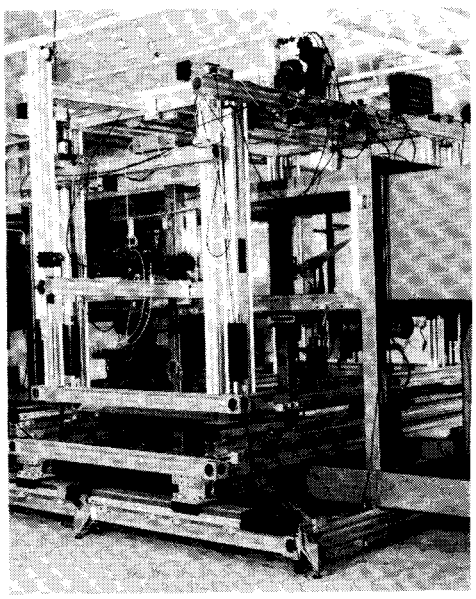
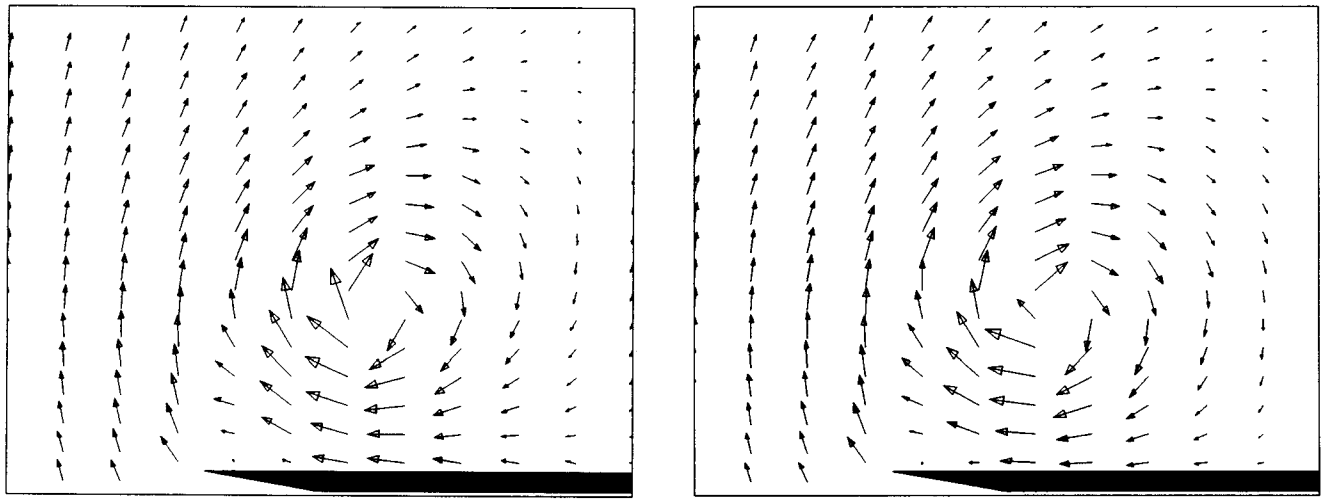


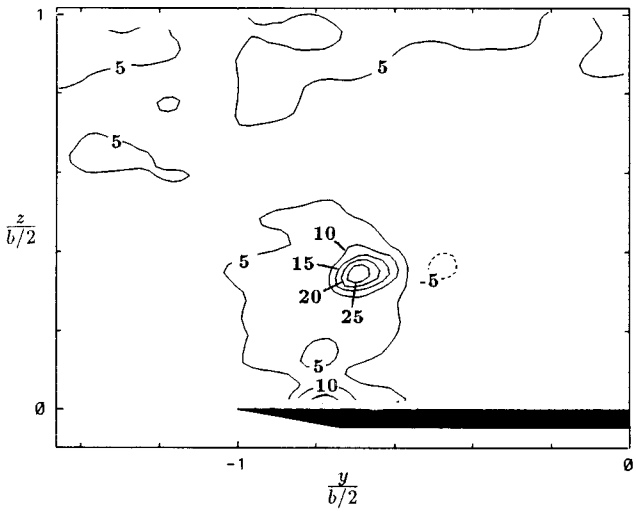
Figure 12. Photograph of the 3-component LDV traversing system.



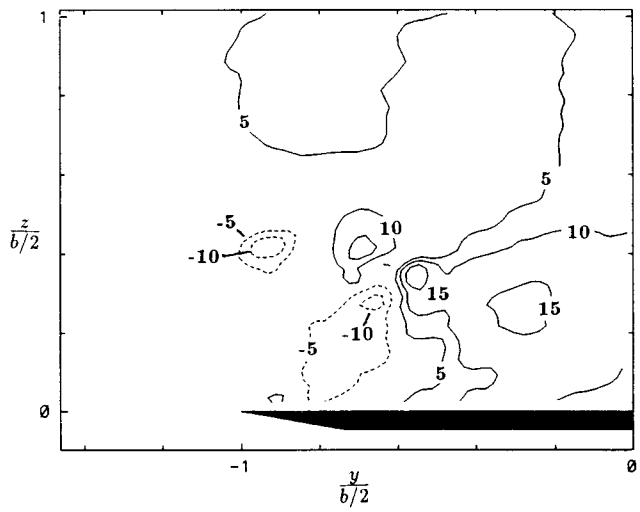
a). 5-hole probe measurements

b). LDV measurements

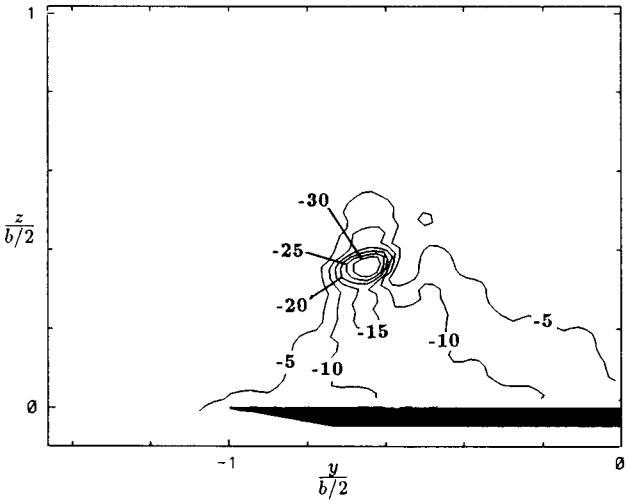
Figure 13. Cross flow velocity vectors over 75° delta wing; α =20.5° , R_n = 1.0x10^6, x/L=0.9



a). u-component



b). v-component



c). w-component

Figure 14. Per cent differences between measured velocities; α =20.5° , R_n = 1.0x10^6, x/L=0.9

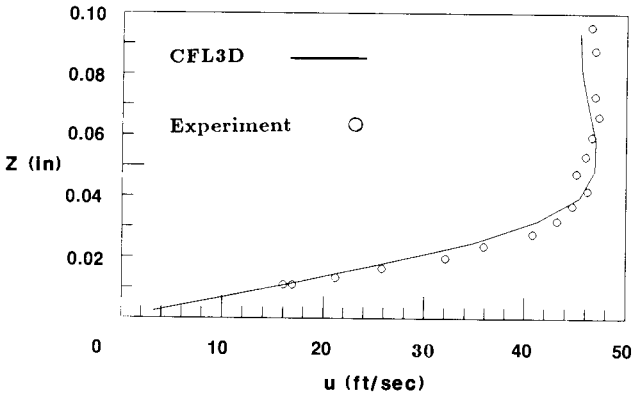
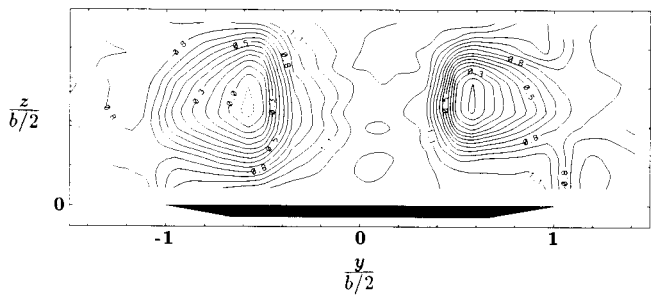
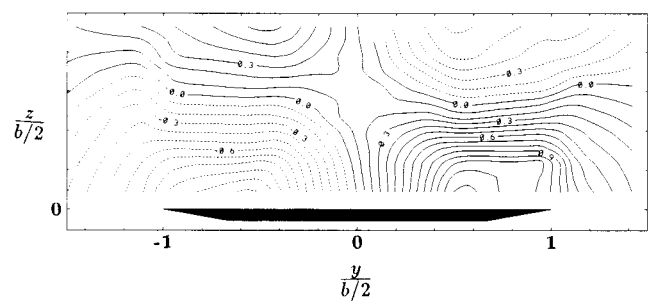


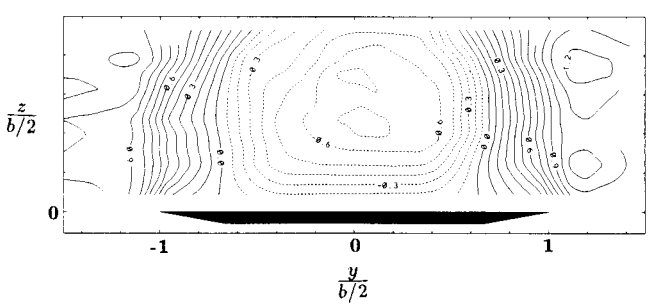
Figure 15. Boundary layer profile over 75° delta wing;
α =20.5° , R_n = $0.5x10^6$, x/L=0.9, $\frac{y}{b/2}$ = 0.02



a). u-component



b). v-component



c). w-component

Figure 16. LDV measurements over 75° delta wing;
α =40.0° , R_n = $1.0x10^6$, x/L=0.7