AIAA 2001-0456
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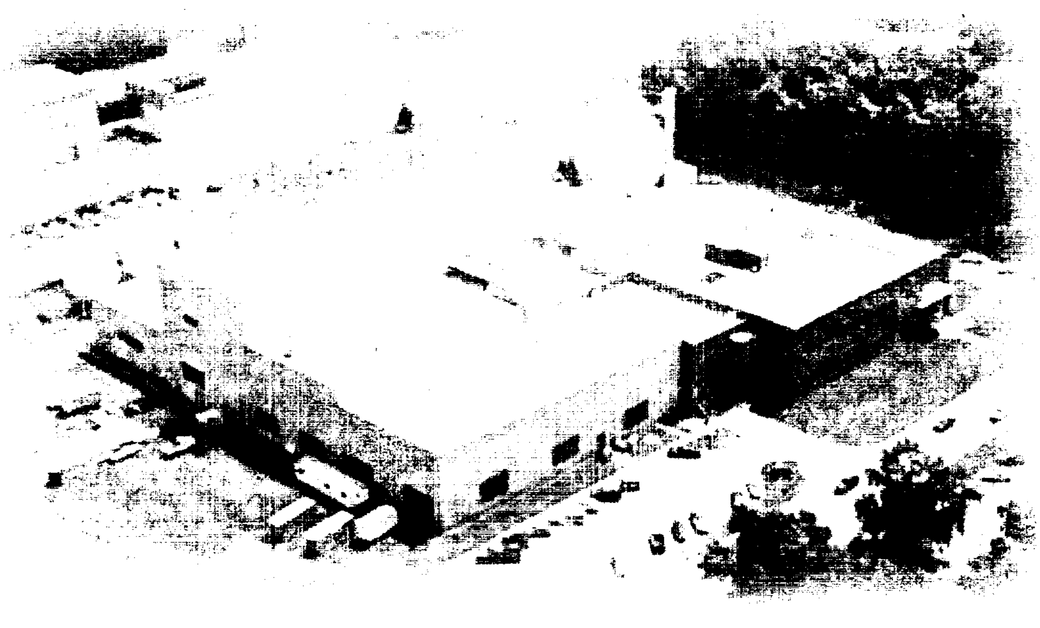

39th AIAA Aerospace Sciences Meeting & Exhibit
January 8-11, 2001 Reno, NV

Langley Research Center's Unitary Plan Wind Tunnel: Testing Capabilities and Recent Modernization Activities

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Abstract

Description, capabilities, initiatives, and utilization of the NASA Langley Research Center's Unitary Plan Wind Tunnel are presented. A brief overview of the facility's operational capabilities and testing techniques is provided. A recent Construction of Facilities (CoF) project to improve facility productivity and efficiency through facility automation has been completed and is discussed. Several new and maturing thrusts are underway that include systematic efforts to provide credible assessment for data quality, modifications to the new automation control system for increased compatibility with the Modern Design Of Experiments (MDOE) testing methodology, and process improvements for better test coordination, planning, and execution.

Introduction

In 1949 the U.S Congress approved a plan, known as the Unitary Wind Tunnel Plan Act, to establish a series of national facilities that would provide experimental aerodynamic support to industry, the Department of Defense, and other government agencies (see NACA, 1956). The plan outlined the development of five wind tunnel facilities. One of the facilities designed and built in the late 1940's and early 1950's, as part of this plan, was the NASA Langley Research Center's (LaRC) Unitary Plan Wind Tunnel (UPWT). Construction of the LaRC UPWT was completed and the facility became operational in 1955. It has remained in continuous operation, except for periodic maintenance, since that time. Throughout it's history the LaRC UPWT has contributed to developmental tests of virtually every supersonic military and industry aircraft, missile, and spacecraft to have become operational in the United States inventory. An overview of a modest portion of these developmental research tests, conducted in the UPWT on high speed vortex flows, is presented in Wood, et al, 2000. This work documents results from an assorted collection of high-speed configurations tested over the past 45 years.

Research testing in the UPWT over these many years has provided for configuration assessment and optimization on the aerodynamic characteristics of numerous concepts. The facility also possesses a unique heat-transfer capability that has been used modestly in the past to assess aerothermodynamic characteristics.

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Contributions include database development for a number of supersonic fighter aircraft and missiles, Space Shuttle Orbiter, National Supersonic Transports, High Speed Research, Personnel Launch Systems, Reusable Launch Vehicles (X-33, X-34, etc.), Crew Return Vehicle (X-38), Hyper-X (X-43), and many others. LaRC UPWT contributions include both database development during the configuration design screening process, a first phase in configuration selection for a particular mission, and benchmarking, aerodynamic and aerothermodynamic configuration information acquired and published in flight databooks for the selected mission concept.

The purpose of this paper is to present a brief description and overview of the LaRC UPWT capabilities and measurement techniques, discuss data quality and productivity initiatives, and provide information on recent upgrades to the facility. In addition, discussion of future approved and proposed upgrades to the facility and data acquisition and reduction systems is included as well as a brief overview of an activity designated as enhanced communication capabilities for test coordination and planning.

Discussion

Facility Capabilities

The Unitary Plan Wind Tunnel (UPWT) (Jackson, et al, 1981 and Wassum and Hyman, 1988) is a closed-circuit continuous flow pressure tunnel with two test sections that are nominally 4 feet by 4 feet in cross section and 7 feet long. A photograph of the facility is shown in figure 1. The primary elements of UPWT are a 100,000-horsepower compressor drive system, a dry air supply and evacuating system, a cooling system, and the necessary interconnecting ducting to produce the proper air flow through either of the two test sections. A general layout of the facility is illustrated in figure 2. The Mach number range is approximately 1.50 to 2.86 in Test Section 1 and 2.30 to 4.63 in Test Section 2. The stagnation pressure can be varied up to a maximum of approximately 50 psia in Test Section 1 and approximately 100 psia in Test Section 2. The low and high Mach number nozzles are of the asymmetric sliding-block type. By moving the lower sliding nozzle block the nozzle throat-to-test section area ratio is varied, thus providing continuous variation of Mach number. Figure 3(a) presents a photograph of the modeled sliding-block nozzle configuration. The second-minimum area is controlled by moving hinged sidewalls to provide the proper constriction to stabilize the normal shock downstream of the test section at the various operating Mach numbers.

In order to cover the entire Mach number range for each test section, the tunnel duct configurations must be altered to provide the compression ratio. Six centrifugal compressors are used in five tunnel configurations or modes, and the tunnel operating modes are available for only one test section at a time. Test Section 1 has two modes within which the Mach number is varied from 1.50 to 2.16 and 2.36 to 2.86, respectively. Three modes exist in Test Section 2 within which the Mach number is varied from 2.30 to 2.96, 3.00 to 3.71, and 3.83 to 4.63, respectively. Figure 4 provides an overview of the UPWT operational characteristics. For any specific Mach number the upper limit of Reynolds number is established by drive power and stagnation pressure limits. The operating range is separated into the five operational modes. The upper limit of operational Reynolds numbers is established by the overload capability of the main drive system. The lower limit is an indication of the supersonic flow stability characteristics at reduced pressure over the Mach number range. Between compressor modes for Mach numbers of 2.16 to 2.36 and between modes for Mach numbers of 3.71 to 3.83, the compressor configurations can not produce the required tunnel pressure ratio to assure stable supersonic test conditions. Typical unit Reynolds numbers for testing at UPWT are 2.0 to 4.0 million per foot, although a range of unit Reynolds numbers from 1.0 to 5.0 million per foot can be easily accommodated. A Reynolds number of 6.0 million per foot is possible on a transient basis but not recommended because of tunnel drive system operational limits. The tunnel stagnation temperatures are typically 125 deg. F and 150 deg. F depending on the mode of operation.

Several methods to support the model have been used, but the basic mechanism is a horizontal wall-mounted strut that is capable of forward and aft travel of over 3 feet in the streamwise direction (fig. 3(b)). A main sting support is attached to the strut and has lateral traverse and sideslip motion of +/-20 in. and +/-12 deg., respectively. Forward of the main sting support is the angle-of-attack mechanism, which provides pitch motion from −15 to +30 deg. A roll mechanism can be installed ahead of the pitch mechanism to provide continuous roll with a 357 deg. range. The model is mounted to the roll mechanism or the pitch mechanism by means of a wide assortment of available stings. The test section stagnation pressure is derived from one of two pitot probes located in the tunnel settling chamber. A vacuum-referenced, Ruska Series 6000 quartz differential pressure transducer measures each settling chamber pressure. Tunnel humidity is monitored using a General Eastern SPECTRA L1 Hygrometer. An Instrulab 25 ohm platinum resistance thermometer measures tunnel total temperature. No corrections for thermal transfer, flow losses or other dissipative effects are applied to these tunnel measurements.

Testing Technique Capabilities

Extensive experience in the application of an increasing number of testing techniques have been developed and honed within the UPWT over many years of testing. In recent years as a result of improved electronics (digital CCD cameras, computers, and computer processing speed, etc.) and drastically increased digital storage capabilities, point measurement techniques are being rapidly replaced by dramatically improved video-based techniques capable of acquiring extensive global information. In Erickson, 2000, a comprehensive overview of "conventional" as well as a number of video-based optical measurement techniques employed at the LaRC UPWT is presented. Discussions emphasize the implementation and application of these test techniques at supersonic speeds, but most of the techniques are applicable to any speed regime and any wind tunnel facility. A detailed account of carefully defined and executed test processes involving test preparation and model set-up, model attitude measurement techniques, strain-gauge balance checkout and utilization, "conventional" pressure-scanning instrumentation, and video-based optical techniques for examining and measuring on and off surface flowfield effects is provided. In addition to the techniques described above, descriptions and examples are provided of several methods used at UPWT to obtain unique aerodynamic measurements, including a missile testing apparatus, store carriage test bed, flutter panel, sonic boom apparatus, dynamic stability rig, captive trajectory apparatus, flow-field survey probes, and reaction control systems. A brief list of conventional and optical-based techniques applied at the UPWT is presented, subsequently. UPWT testing in the recent past focussed on the High Speed Research (HSR) Program and afforded a concentrated testing effort that helped to increase facility staff proficiencies in aerodynamic performance and stability and control testing as well as a number of flow visualization techniques. The capabilities and lessons learned via the HSR program will be applied to future configuration testing. Following is listed a number of test capabilities and measurement techniques utilized at the facility:

- **Forces and moments**
- – Performance
- – Stability and control
- **Pressure measurements (Discrete)**
- – Electronically Scanned Pressure (ESP) pressure scanners
- – Pressure transducers
- **Optical Surface Measurement Techniques**
- - Pressure sensitive paint (PSP)
- - Video Model Deformation
- - Infrared Thermography
- - Projection Moire Interferometry
- **Optical Off-Surface Measurement Technique**
- - Doppler Global Velocimetry
- **On- Surface Flow Visualization Techniques**
- - Sublimating chemicals
- - Surface oil flow
- - Oil Film Interferometry
- - Colored water flow
- **Off- Surface Flow Visualization Techniques**
- - Schlieren
- - Focusing Schlieren
- - Shadowgraph
- - Laser Vapor Screen
- **Configuration studies**
- – Nacelles, inlet pitot rake surveys
- – Wing planform/contour variations
- – Aftbody drag characteristics
- – Wing/fuselage boundary layer trip/transition
- – Pressure signature mapping (sonic boom)
- – Remote control missile apparatus
- – Store carriage drag measurements
- – Captive trajectory apparatus
- – Flutter suppression
- – Dynamic stability test rig
- – Probe-type flowfield surveys
- – Reaction control system (RCS)

Examples of a limited number of these visualization and measurement techniques are presented in figs. 5 to 8.

Often, techniques are employed in concert to provide a combined set of diagnostic analysis tools for assessing local (on-surface discrete measurements) and global (on and off surface) flow field effects. An example taken from Erickson, 2000 illustrates the application of PSP at UPWT to determine the effects of surface porosity on the vortex-dominated flow about a general research fighter configuration shown in figure 9. The forward portion of the model is a flat-plate leading-edge extension (LEX) that can be configured as a "solid" surface or a porous surface having a 12% porosity level relative to the LEX exposed area. The LEX was mounted to a 65-degree cropped delta wing to which a centerline vertical tail or twin, wing-mounted vertical fins were installed. The right-hand wing incorporated three spanwise rows of upper surface static pressure taps that were used to perform in-situ calibration of the PSP. Fully processed images comparing the solid and porous LEX intensity field images are shown in figure 10, which corresponds to Mach=1.6, Re/ft=2.0 million, and $\alpha = 8^{\circ}$. The porous LEX configuration exhibits a single, broader vortex pressure signature, and the manner in which the wing vortex system interacts with shock waves from the wing-mounted vertical fins is also affected by the porosity. The corresponding PSP and ESP pressure distributions at the 80% chord station are compared in figure 11. PSP and ESP pressure distributions reveal a very good global calibration of the paint. In addition, the pressure distributions effectively capture the effect of LEX porosity on the vortex-dominated flow at supersonic speeds. Figure 11 also presents a correlation of the test techniques. Laser Vapor Screen (LVS), as a flow visualization technique, adds information concerning the associated cause of pressure variations across the chord. Hence, a better realization of the off-surface flowfield effects on the pressure distributions is acquired. Correlation of measurement techniques, like LVS, PSP, and ESP and others are used routinely at the facility for examining cause and effect of off-surface flow phenomena on local/global surface measurements.

Data Acquisition/Recording System

The UPWT Data Acquisition System (DAS) consists of a MODCOMP REALSTAR 2000 Open Architecture system utilizing four 25-MHz Motorola 88100 CPU's in a tightly coupled, fully symmetrical processor configuration. This system supports both data acquisition and real-time data reduction. Each test section possesses a dedicated MODCOMP. Each MODCOMP is interfaced to a dedicated NEFF 620-500/600 DAU that provides 128 analog channels and 32 digital channels. The analog channels have software selectable names (8-character), ranges (5 to 10240 mv), filters (1,10,100,1000 Hz), and equation forms (linear, polynomial, arc sine, etc.) A digital subsystem is included within each system and is equipped with custom designed "smart cards" for RUSKA pressure gages, linear displacement transducers, digital temperature gages, Datex shaft encoders, resolver-to-digital converters, and a dew point interface. There are also 5 digital thumbwheel channels and up to 40 digital constants included in a digital panel. These channels are also configurable for names and equations.

Each test section is equipped with a dedicated Pressure Systems Incorporated (PSI) 8400 system for measuring up to 1024 pressures. Thirty-two (32)- and forty-eight (48)-port ESP modules are available with full-scale ranges of 1, 5, 15, and 30 PSIA and 1, 5, 15 PSID. Both raw data and computed Engineering Units (EU's) may be displayed and plotted at a rate of approximately 5 times per second. Data frame recording rates are configurable from 1 to 100 frames per second for the analog and digital and at 1 to 20 samples per second for ESP data. Standard MODCOMP data sampling rates for all NEFF analog input channels is 30 frames/sec, averaged over a 2 second interval for each data point (60 frames averaged/point). Standard electronically-scanned pressure (ESP) data sampling rate between the MODCOMP and the PSI 8400 SP is 10 frames/sec, which is nominally averaged over a 2 second interval (20 frames averaged/point). The raw frame data and the average data are recorded to a raw data disk file that is re-processed off-line. Average raw data and EU's are recorded on an archive file that is saved for the entire test. Data from the archive files may be tabulated and plotted in real-time using X-window terminals for graphical comparisons. Other files may be added as User Data Files which originate from theory, from other tests, or from the present test data that has been edited and re-computed off-line. Final data reduction and post-processing functions are accomplished on Sun Ultra 2 SPARC II workstations linked to the Langley Research Center network. Secure data processing operations are available and an alternate scheme is employed for this test type. An additional "quick look" option is available whereby real-time data may be sent to other remote computer systems via RS-232, IEEE-488, or socket (TCP/IP Ethernet) interfaces.

Future Data Acquisition System Upgrades

The Next Generation Data Acquisition System (DAS) has been designed and is presently in the final developmental stages. The Next Generation DAS is a low-cost data acquisition system developed by the Data

Acquisition and Information Management Branch (DAIMB) at Langley. It consists of four major components: Acquisition, Computation, Display, and Data Reduction. The Acquisition and Computation Components can reside on separate computer systems in a distributed configuration, or can be combined onto a single computer system for a centralized configuration. The Display Component consists of one or more computer systems that are used as the operator consoles for the Next Generation DAS. The Data Reduction Component operates offline and is used with the Computation Component for post-test data reduction. User interaction is accomplished through the Display Component systems.

The Acquisition and Computation Components are currently supported on personal computer (PC) platforms, using Intel Pentium III processors or equivalent, running Windows NT 4.0 or Windows 2000. The Display Component can reside on PCs or can operate on Sun workstations running Solaris, or Compaq Alpha systems running Digital UNIX. Java 1.2 is required for any system running the Display Component. Data acquisition hardware supported includes the NEFF System 620 Series 500 analog and digital inputs and the NEFF System 470 for both SCSI and IEEE interfaces, and the PSI System 8400 for both network and IEEE interfaces.

The Computation Component receives raw data values from the Acquisition Component and converts the values to engineering units (EUs). The Computation Component also performs complex computations on these engineering unit values to produce "pseudo channels" for these computed values. User-defined computations can be specified, from simple equations, to complex computational algorithms using C, C++, or MATLAB programs. Data can also be transmitted to, or received from, external computer systems for additional user processing and control. Physical channel data (in engineering units), standard computed parameters, and user-defined computed values are recorded in a Microsoft Access database for report generation, displays, plotting, archiving, and user processing and analysis.

The Display Component receives converted and computed data from the Computation Component. The data are sent to one or more Display Component systems through a network interface. Real-time data values are transmitted using a multicast network protocol to reduce network load. With multicasting, data values are transmitted only once, but may be received simultaneously by multiple displays. The data values are formatted locally, relieving the host computer(s) from the burden of complex graphical processing. The Display Component also provides a graphical user interface (GUI) that allows the user to control the operation of the system.

The Data Reduction Component retrieves the raw data files created by the Acquisition Component to allow previously acquired data to be reprocessed using different user conversions, coefficients, or other configuration parameters. The Data Reduction Component can either work with the Next Generation DAS or operate in a stand-alone configuration called the NT Data Reduction System. The NT Data Reduction System is a Windows 2000 or Windows NT-based post-test data reduction and analysis system that allows users to easily re-compute, analyze, and visualize experimental test data. It uses the existing Langley Open Architecture (OA) raw data files and provides a standardized program for post-test processing. The NT Data Reduction System was developed to standardize post-test processing across multiple wind tunnels and structural testing facilities at the Langley Research Center.

Both the Next Generation DAS and the NT Data Reduction System uses many commercial off the shelf (COTS) software products to reduce software development and maintenance costs, resulting in a lower cost throughout the complete life-cycle of the systems. Most of these products are optional and provide additional capability at a low cost.

Synergism of Facilities within the Aerodynamics, Aerothermodynamics, and Aeroacoustics Competency (AAAC)

One of NASA Langley's greatest capabilities is a collective set of wind tunnels providing the aggregate centralized capabilities to assess and evaluate aerodynamic and aerothermodynamic performance characteristics of a vehicle concept across the speed range. The Langley AAAC provides the comprehensive testing capabilities of a suite of facilities operating over speed regimes encompassing subsonic, transonic, supersonic, and hypersonic testing. Each facility strives to provide superior data quality assurance, testing capabilities, and an exhaustive battery of testing techniques. (A number of these facilities including corresponding capabilities are presented in the following references: Jackson, et al, 1981, McGhee, et al, 1984, Capone, et al, 1995, Gentry, et al, 1990, Micol, 1998, Erickson, 2000, Fuller, 1981, Foster, et al, 1996, Igoe, 1996, Bobbitt, et al, 2001, Merski, 1998, and Merski, 1999.) Figure 12 presents a compilation of the operational characteristics achievable from subsonic through hypersonic test conditions and represents only a limited portion of the total of the many test facilities managed by AAAC. A Shuttle Orbiter flight trajectory for STS-1 is included whereby Reynolds number has been referenced to the full-scale vehicle length. The key indicates typical scaled model sizes tested within each facility. Other examples of contributions to the development of vehicle concept experimental databases include the Shuttle Orbiter, National Aerospace Plane, Fighter Aircraft, HL-20, X-33, X-34, HSCT, HSR, X-38, X-43, and many others.

Historically, these facilities have been, and continue to be, used for configuration screening database development exercises occurring during Phases I activities of new initiatives like Reusable Launch Vehicle (RLV). Likewise, these same facilities are used to produce configuration benchmarking data such as occurs during Phase II (i.e., development of configuration aerodynamic and aerothermodynamic flight databooks). As an example and presented in fig. 13(a), approximately 90 percent of the experimental aerodynamic database for the HL-20 was developed within Langley facilities. (HL-20 was originally proposed for the Personnel Launch System (PLS). Later it became a predecessor to the Assured Crew Return Capability that was subsequently defined Crew Return Vehicle, i.e., ACRC/CRV, a vehicle proposed for crew emergency egress from the International Space Station. The configuration selected for that mission is now known as the X-38.) For this study various scale models were manufactured and tested in the Langley facilities to define the concept's aerodynamic performance characteristics across the speed regimes. Figure 13(b) presents a summary of trimmed aerodynamic characteristics over the Mach range. A complete discussion of the databases developed for this configuration is presented in Ware, et al, 1993. (A compilation of aerodynamic and aerothermodynamic data developed for this configuration is presented in the Journal of Spacecraft and Rockets, 1993).

A more recent example of configuration screening occurred during Phase I studies of the X-33, Reusable Launch Vehicle/Advanced Technology Demonstrator (See Miller, 1999). Three different industry concepts proposed for RLV/X-33 Phase I were evaluated simultaneously. This collective set of concentrated test capabilities was heavily utilized to generate aerodynamic and aerothermodynamic information for assessing and optimizing the performance of these industry concepts. In a number of these cross facility tests a single model, balance, and sting assembly was used to acquire performance data at subsonic, transonic, supersonic, and hypersonic test conditions in order to meet program goals for this fasted-paced Agency program (Woods, et al, 1995). Figure 14 illustrates one example of cross facility testing in the development of pitch characteristics for a vertical take-off/vertical landing (VT/VL) RLV concept performed during Phase I.

The AAAC facilities also supply configuration aerodynamic/aerothermodynamic information for establishing flight databooks as demonstrated by the example presented in fig. 15(a) for Phase B studies of the X-34 Small Reusable Technology Demonstrator under the auspices of the RLV program. Again, approximately 90 percent of the experimental database for the flight aerodynamic databook and 100 percent of the experimental database for the flight aerothermodynamic databook was accomplished via cross facility testing in the subsonic (LTPT), transonic (16 ft. TT), supersonic (UPWT), and hypersonic (20-Inch M6/31-Inch M10) test facilities. Figure 15(b) presents the pitching moment characteristics for X-34 over a Mach number range from 0.4 to 6.0. (For a discussion of the X-34 experimental aerodynamic and aerothermodynamic databases see Brauckmann, 1999, Pamadi, et al, 1999, Pamadi, et al, 2000, and Miller, 1999). A compilation of aerodynamic and aerothermodynamic data developed for this configuration is presented in the Journal of Spacecraft and Rockets, 1999.)

Likewise, specific test techniques have been employed to generate unique contributions to flight databooks. As one example, distinct configuration data were acquired using the capabilities of the UPWT and the 16-ft TT. A 0.02-scale X-33 model was tested in both facilities to evaluate a Flush Air Data Sensing (FADS) system concept. FADS airdata are inferred from nonintrusive surface pressure measurements (Cobleigh, et. al., 1999). The airdata measurement system can be extended into the hypersonic flow regime and avoids damage to small radius flow-sensing probes caused by extreme hypersonic heating. (Small probes may be used for lower speed regimes to acquire the needed flight parameter data.) The airdata parameters provided by the FADS system include Mach number, angles of attack and sideslip, airspeed, and altitude. There are three calibration parameters which require evaluation for the FADS system: the position error, the angle of attack flow correction angle, and the angle of sideslip flow correction angle. For the preliminary design, these calibration data are obtained from wind tunnel testing. The wind tunnel model featured 21 static pressure orifices in an array on the nose cap and pressures were measured using an internal 32-port, 10 psid ESP module (used in absolute mode). A close-up image of the model instrumented nose cap is shown in figure 16. The results from the UPWT testing spanning the Mach number range of 1.6 to 4.5 complemented a data base acquired at Mach=0.25 to 1.20 in the 16-Foot Transonic Tunnel. This experimental database resides within the X-33 RLV Aerodynamic Flight Databook and represents a unique data set (See Erickson, 2000 and Scallion, 2000 for additional details.).

Synergism of the UPWT and the Aerothermodynamic Facilities Complex (AFC)

In another example, unique configuration data sets were acquired using the capabilities of the UPWT and two facilities of the AFC, namely the 20-Inch Mach 6 and 31-Inch Mach 10 Tunnels (Micol, 1998). Tests of a 0.01-scale X-33 RLV Reaction Control System (RCS) model were performed (fig. 17). RCS is used during the hypersonic and supersonic reentry portions of the trajectory. Over these speed regimes, aerospace vehicles return at high angles of attack and for these particular conditions a loss of conventional control surface effectiveness is experienced due to a low-energy wake "blanketing" effect (Erickson, 1995). As a result, the use of reaction control system

(RCS) jets is necessary to control such vehicles during these phases of flight. Wind tunnel experiments to simulate RCS jets and to measure their direct (thrust) and induced (aerodynamic) effects were performed over this speed range with a single model equipped with a flow through balance and sting combination. The database developed during these tests represents the total of RCS testing data for this configuration to date and has been incorporated into the X-33 RLV Aerodynamic Flight Databook.

The preceding examples demonstrate the utility of this aggregate collection of capabilities for fasted-paced configuration assessment and optimization and/or comprehensive configuration aerodynamic and aerothermodynamic flight databook development. The centralized assemblage of these facilities fosters database development across the speed range (i.e., from subsonic through hypersonic test conditions) utilizing a variety of model scales or a single scaled model to meet program requirements and objectives. The combined capabilities of the AAAC facilities are well suited for addressing both parametric aerodynamic and aeroheating studies required in the early design and assessment stages or for development of benchmarking databases as required for future national programs, such as 2nd and 3rd Generation Reusable Launch Vehicle.

Data Quality/Productivity Initiatives

Data Quality Assurance (DQA)

The Wind Tunnel Enterprise (WTE) at Langley Research Center has committed itself to supporting national programs developed in partnership with other NASA Centers, other government organizations, and industry. This commitment has required entirely new levels of customer trust in the results produced by the tunnels and led to consolidation of most of the tunnel assets into the WTE, which includes the Unitary Plan Wind Tunnel. One of the more critical tasks assigned to each of the WTE tunnels is the improvement of data quality assurance to levels suitable for achieving national standards for all testing.

In 1995, a methodology based on statistical quality control was adopted to confidently and credibly quantify data quality for data acquired during tests conducted within facilities participating in the WTE. In an effort to add credence to the claim of superior data quality assurance, (see above statements) the LaRC UPWT, as part of the data quality assurance (DQA) program implemented by the WTE, is currently immersed in this comprehensive DQA process. Check standard testing, a surrogate process of testing a stable artifact at frequent intervals is implemented to determine measurement uncertainty and to remove any doubt that the measurement process is stable and meaningful in a statistical sense.

Over this 5-year period UPWT has participated in this activity by performing periodic tests of the supersonic transport model represented in figure 18(a). This configuration has been tested on a regular basis in UPWT Test Section 2 and has served as an interim check standard model. (An existing general research fighter model has been identified as the new check standard for UPWT, and its initial testing began in mid-2000, see fig. 19.) "Quick-look" statistical quality control (SQC) charts are prepared by the DQA team to illustrate the back-to-back polar repeatability within a single test entry (see Hemsch, et al, 2000). Figure 18(b) presents an example of a within test scatter plot using data from a previous test of the supersonic transport model. Within test repeatability is shown for three back-to-back runs executed at the beginning and end of the test. Data are plotted in the standard manner to provide a clearer overview of within test repeatability. (Hemsch, 2000 provides a detailed discussion of the application of the DQA process to repeated data within a test in order to ascertain statistical quality control and provide indication of any potential problems associated with the data sets. Therefore, the present paper will focus discussion on the DQA methodology as applied to back-to-back repeat runs for 5 repeat test entries of the check standard model performed over the past years (following paragraph). Within test repeat data sets are analyzed in a similar fashion.) Scatter plots, like the one presented and "quick-look" SQC charts, provide a rapid first-order assessment of the data repeatability and can flag problems or changes that might have been introduced within and between the repeat groups. Five test entries of the supersonic transport model at UPWT over a period of several years have indicated that data reproducibility of normal force, axial force, and pitching moment coefficients (ΔC_N, ΔC_A, and ΔC_m,) in the attached flow regime are typically +/-0.001, +/-0.00005, and +/-0.0001, respectively.

For each check standard model test, a nominal angle of attack is chosen for control chart analysis. An angle of attack in the middle of the attached flow region is selected under the assumption that the attached flow region corresponds to the region of minimum scatter. The angle of attack chosen for analysis of the UPWT check standard model tests is 2.5 deg. where the flow over the wing remains attached. At very low angles of attack where flow separation occurs along the lower surface, or at higher angles of attack where upper surface flow separation occurs, the data scatter expands because of increased model dynamics (also, flow separation dynamics). Control charts like the ones presented in figure 20 are created from off-line analysis tools that interpolate the normal force, axial force, and pitching-moment coefficient data to the nominal value of angle of attack, average the data, and subtract the averages from the interpolated data. Each data point shown corresponds to the linear interpolation of data from three back-to-back runs for the nominal angle of attack. The interpolation takes out any scatter due to setpoint variation. Based on the work by Shewhart, an upper and lower control limit is established for the groups of points corresponding to roughly 300:1 odds. Based on these odds, for a process in statistical control, the likelihood that points will be found outside these limits is extremely small. Also, if any points occur outside these limits or if unusual patterns in the points are noted whose likelihood is beyond the 300:1 odds, then the process is determined not to be in control. Similarly, if enough data is acquired, the points are located within the limits, and no unusual random-like behavior is noted, then the process is defined in statistical control. Also, if the process is in control then the properties of any future point samples taken would be predictable. Examination of data for repeated tests of the supersonic transport, indicate that data for the 5 check standard tests fall within the limits on each chart. Thus, there is no evidence of the lack of statistical control for either repeatability (back-to-back runs within a test) or reproducibility (test-to-test variation) of test data acquired (Hemsch, et al., 2000). Reproducibility is determined by multiple entries in the same tunnel over a notable period of time (i.e., years). However, more data groups need to be gathered to claim definitively that the balance measurement process is clearly in statistical control.

As an additional part of the test process and employing a scaling method, these check standard results are applied to repeat-run data sets obtained during customer tests at the beginning and end of the test (Hemsch, et al., 2000). Statistical information from the check standard tests and the customer test are compared to assure that the repeatability and reproducibility of the customer data fall within expected limits. From this information, a statement addressing customer data repeatability and reproducibility is developed. A detailed discussion of the data quality assurance program adopted by the LaRC WTE (and the LaRC UPWT) is presented in Hemsch, et al, 2000.

Modern Design of Experiments

The Modern Design Of Experiments (MDOE) test methodology has been demonstrated by NASA LaRC to generate higher-quality research results at less cost and in less time than the conventional one-factor-at-a-time (OFAT) test method routinely used in wind tunnel testing. This testing methodology has the potential to significantly reduce the amount of data required in wind tunnel tests compared to traditional OFAT test methods, thus reducing test time and test costs.

Conventional OFAT wind tunnel testing attempts to hold all variables constant while sequentially changing a single independent variable over the range of levels. A typical OFAT wind tunnel test to characterize the aerodynamic performance of a high speed civil transport model, for example, might feature "alpha sweeps" at constant Mach number, Reynolds number, and sideslip angle. These sweeps ensure that response variables of interest (forces, moments, etc) change systematically with *time* as well as with the independent variable – alpha in this case. This has the advantage that it maximizes data acquisition rate, a popular productivity measure in 20th-century wind tunnel testing, but it also ensures that the true alpha dependence will be confounded by any other systematically varying phenomena that can influence response measurements. That is, the focus on high data acquisition rate that motivates sequential set-point ordering of the independent variables leaves the OFAT method vulnerable to an unseen superposition of systematic errors that might occur as a result of drifts in the tunnel operating condition set points (total pressure, temperature, dewpoint), strain-gauge balance output, nozzle block and wall settings, sideslip angle, subtle flow angularity changes, etc. For this reason, to achieve the highest quality results in conventional OFAT testing a state of *statistical control* must exist while the data are acquired. In such a state, sample means are stable (time-independent), so that the only factors influencing how response measurements vary are the independent variables changed intentionally by the researcher.

MDOE methods were introduced early in the 20th-century (in other research areas besides aeronautics) to free researchers from the burden of establishing a state of statistical control as a prerequisite for high-quality data acquisition under real-world conditions, where such a state can be difficult to guarantee. DeLoach, 1998 demonstrates how, in the presence of systematic error, the quality of an experimental result can be influenced by the order in which the independent variables are set. Altering set-point ordering is one of a number of tactical defenses against systematic variation employed in the MDOE method. (See DeLoach, 1998, DeLoach, Jan. 2000, DeLoach, June, 2000.)

MDOE features the processes of blocking, randomization, and replication to enhance the quality of data obtained in wind tunnel testing. Block effects arise in wind tunnel testing when response variables such as balance forces and moments, wing surface pressures, wing twist distributions, etc. measured in one block of time differ significantly from measurements made in another block of time under circumstances expected to yield identical results within experimental error. Blocking the test matrix – partitioning it into smaller segments with points that will be run without interruption -- permits between-block systematic variations to be eliminated in the analysis as a source of otherwise unexplained variance in the data, thus enhancing overall precision. Such between-block offsets can be caused by overnight changes in the instrumentation and data systems, subtle between-shift operational or process changes in multi-shift operations, and so forth.

Randomization is simply the act of setting the levels of the independent variables in random order to address within-block systematic variations. It has the effect of converting undetectable systematic variation to an additional component of random error. Because these random errors are identically and independently distributed about the underlying independent-variable functional relationship, they do not distort that relationship. They are also easy to detect and can be reduced to customer-specified levels by ordinary replication.

Replication features the acquisition of repeated data points acquired under conditions that permit an equal chance for all factors that can contribute to the random error to exert their influences. Acquiring genuine replicates often entails making measurements at random intervals throughout the test, with intervening changes in the independent variables having taken place. Replication is an effective tactical defense against random error because the variance in an average of N genuine replicates is inversely proportional to N. As long as the errors are all random (ensured by randomization that removes within-block systematic error and blocking that removes between-block systematic error), the precision of an experimental result can be made arbitrarily good by acquiring a sufficient volume of data. Conversely, assuming that MDOE tactical defenses against systematic error are employed, any customer-specified precision requirement translates into a specific corresponding data volume requirement. This fact can be exploited to scale resources to customer-specified precision requirements.

An extensive range of different formal experiment designs is available to satisfy a wide variety of experimental circumstances, but not every MDOE test matrix is suitable for every test because of wind tunnel operating constraints. In a hypothetical test at UPWT, for example, the desired response variable might be the yawing moment produced by vertical tail rudder deflection on a fighter model. Mach number, Reynolds number, angle of attack, angle of sideslip, and rudder deflection comprise the independent variables. It is assumed that control surface changes are manual. The time required to secure the test section for running, acquire pumpdown zeroes, start flow, and achieve stable operating condition set points may be an hour or more. Randomization on the rudder deflection would require frequent access to the test section, which would require dropping flow, that is, bringing the tunnel back to a low energy wind-off state, acquiring pumpdown and atmospheric zeroes, model change, more wind-off zeroes, flow start, and flow condition stabilization. The latter process would likely require 1-1.5 hours. Such facility power costs and time constraints are factors that must be weighed in the definition of the test matrix. Similarly, randomization on the Mach number is limited by UPWT operational procedures, since a mode change in Test Section 1 requires flow to be dropped in order to reconfigure the tunnel circuit and valving. In Test Section 2, mode changes can be done "on-the-fly" in increasing order, but it is not possible to return to a lower mode without first dropping off and reconfiguring the tunnel circuit. These types of practical constraints at UPWT also exist in other facilities in one form or another. They illustrate an important distinction that must be made among independent variables in an MDOE experiment design, based on how much effort is needed to randomize set-points for those variables. Manually changed control-surface deflections such as the rudder deflection in this example represent a class of factors called "hard-to-change variables" in MDOE designs. Mach number in UPWT tests requiring mode boundaries to be crossed, and Reynolds number changes that require cryogenic temperature cycling in the National Transonic Facility, are other examples of hard-to-change variables. Angle of attack, angle of sideslip, and Reynolds number changes at UPWT are examples of "easy-to-change" variables, so designated because their levels can be randomized relatively easily.

A special class of experiments called split plot designs accommodates mixtures of hard-to-change and easy-to-change variables. In such designs, the easy-to-change variables are randomized in the usual way, while the hard-to-change variables remain fixed. Each fixed combination of hard-to-change variables is then replicated in random order to achieve the protection from systematic variation that is the hallmark of MDOE testing. Split plot designs therefore trade additional data volume for a more convenient treatment of hard-to-change variables.

The implementation of a new automated control system at UPWT, which is intended to improve wind tunnel productivity, has inadvertently posed a road block to effective implementation of an MDOE test matrix (work is underway to resolve this issue and will be discussed subsequently). Specifically, randomizing on the angle of attack requires that whenever the alpha sequence involves changing angle from a high to low value, the model must first be returned to a low-alpha "home" position to ensure that all data set-points are approached from below. This is necessary to ensure that the randomized alpha schedule does not induce aerodynamic hysteresis effects caused by flow separation that can occur at a different angle of attack when alpha is increased than when it is decreased. The UPWT automated test sequence software is not currently flexible enough to accept this type of run sequence without a considerable amount of effort and manual intercession by the facility data operator. Overall "wear and tear" of facility equipment undergoing more frequent cycling is also a factor that cannot yet be assessed. It should be noted that many of the operational constraints typical to a given wind tunnel facility may be adequately resolved by a suitable "cultural shift", while others will have to be dealt with as effectively as possible (via specialized designs that accommodate hard-to-change variables at the expense of additional data volume, for example). The potential of MDOE to provide a higher quality research result, which is the product delivered by the wind tunnel, must be evaluated and exploited as best as possible. The same is true of the resource savings potential of MDOE, achieved by explicitly scaling data volume to customer precision requirements. To accomplish this, more researchers and test facility personnel must become versed in the design, implementation, and analysis phases of MDOE.

The first MDOE wind tunnel experiment at LaRC was conducted in UPWT Test Section 1 in 1997 in which model deformation (wing twist and deflection) was quantified as a function of the independent variables angle of attack, Mach number, and Reynolds number using the supersonic transport model previously shown in figure 18(a). This test was conducted in both the classical OFAT tradition and using MDOE methods. The OFAT design featured 330 data points. The corresponding MDOE design required only 20 data points to obtain information of comparable or higher quality, in terms of 95% confidence interval half-widths. A representative result from this test is shown in figure 21, which illustrates the effect of the angle of attack on wing twist at the 54% span station at a free-stream Mach number of 1.60 and Reynolds number of 3.0 million per foot. The OFAT points are shown with error bars along with the upper and lower limits of the 95% prediction interval for the MDOE response surface at the same Mach number and Reynolds number. "Slices" were taken through the response surface parallel to the angle of attack axis at constant Mach number and Reynolds number to create MDOE equivalents of wing twist versus angle of attack "polars." It is noted that none of the 20 points defining the response surface for wing twist as a function of Mach number, Reynolds number, and angle of attack corresponded to any of the measured OFAT data points in the figure. In this test, the substantial reduction in the number of required data points resulted in approximately 60% fewer wind-on minutes in the MDOE version in comparison to the OFAT method. This initial success was the first of an on-going program at LaRC to exploit the benefits of MDOE.

A more recent application of MDOE was conducted in 1999 in UPWT Test Section 2 to quantify the aerodynamic effects of pressure-sensitive paint and model deformation retroreflective targets applied to the wing upper surface of a high speed civil transport. Results of these tests indicated that the paint effect on drag coefficient was unresolvable, that is, the effect is not distinguishable from zero with 95 percent confidence. Likewise, there was no resolvable effect of the 0.004-inch thick targets on the drag coefficient to within a 95 percent confidence interval. Full details of MDOE application to this test are presented in Erickson, 2000.

Recent Facility Upgrades and Enhancements

A number of facility upgrades and enhancements have been accomplished over the last few years via various funding sources, in particular, WTE re-investment projects, maintenance augmentation, and minor CoF programs. The primary purpose for these upgrades and enhancements was to provide increased capability, reliability, and productivity.

Automatic Test Sequencing

A recently completed FY'98 CoF was proposed to convert facility manual control systems to a Facility Automation System (FAS). The overall plan for FAS was to encompass both model attitude controls and wind tunnel operations. As a first phase, facility automation control enhancements were implemented to automate model attitude and a limited number of tunnel operational system controls and provide the means for Automatic Test Sequencing (ATS). An Experimental Physics and Industrial Control System or EPICS-based control system was selected for this automation project. The UPWT FAS is comprised of three independent control systems. One system is used in the control of tunnel flow conditions and the other two systems are used for stand-alone model positioning control, that is one for each test section. The total of the three systems consists of three HP 700 series host computers and eight VMEbus Extensions for Instrumentation (VXI) chassis networked together. The host computers act as boot servers for the VXIs and provide the graphical user interface (GUI). Each host computer supports four X-Terminal screens in a quad arrangement for displaying the GUI screens and other general and critical information such as status, position, alarms, etc. Control algorithms and a number of monitoring functions reside within the VXI chassis. Each of the three systems contains a SCRAMNET interface card used to provide a fiber optic connection to the Open Architecture DAS computer for the purpose of passing data and command information. Analog and digital I/O boards and a communications link to an Allen Bradley Programmable Logic Controller is also located within the VXI chassis. The tunnel flow control system, under the auspices of FAS but not currently included in ATS, provides automatic control of stagnation pressure, stagnation temperature, and dewpoint temperature. The model attitude control system provides automatic control of model attitude that can be driven by the ATS for alpha/beta or pitch/yaw or pitch/traverse, with axial and roll.

The UPWT completed shakedown testing of the new EPICS-based FAS in late 1999. However, the full potential of the FAS had not been achieved. By implementing a number of control software improvements, tuning field devices for better response, and performing maintenance or replacement of facility control actuators for increased reliability, the overall FAS has been enhanced. Identified improvements resulting from ATS implementation include faster setpoint sequencing and consistency (i.e., factor of 2), improved productivity (polars achievable per hour), increased and repeatable setpoint accuracy, increased model safety provisions via redundant hardware and software limitations, and decreased operator workload that is, less intervention/interaction with the control system. Regarding the tunnel control system, identified improvements include decreased time for tunnel run-up (i.e., from a dormant state to a stabilized test condition) by a factor of approximately 1.5 and improved test condition lock and bandwidth tolerance reductions (i.e., regulating and holding setpoint within a predetermined bandwidth). Others include an enhanced early warning system for possible setpoint problems and decreased operator workload. A second control system upgrade phase is planned in the near future whereby additional tunnel controls for both mechanical and electrical manual control operations will be automated.

Modern Design of Experiments Automation Enhancements

A newly proposed modernization thrust seeks to modify and expand existing automated facility controls to automate MDOE testing. The objective of this facility controls automation project is to address and enhance areas of the UPWT control systems in order to make the facility "MDOE friendly". MDOE enhancements to the ATS software include the following; (1) a file format with tunnel condition and model attitude setpoints within the same run matrix; (2) the ability to specify transition setpoints for efficient re-approaching tunnel conditions and/or model position; (3) the use of an expanded data identification (ID) that distinguishes replicate points and confirmation points for MDOE post processing; and (4) the ability to configure efficient setpoint ordering for pause (i.e., wait while setting certain conditions prior to proceeding to the next block) or simultaneous execution of all setpoints when desired. These areas include extending the capability of the automatic test sequencer (ATS) software, re-tuning and enhancing the control algorithm software, and possibly making adjustments to the facility control actuators for reliable controllability.

To date a number of system controls software modifications have been performed, the GUI enhanced, and shakedown testing completed. The ATS has now demonstrated the ability to operate in either the OFAT mode or the MDOE mode. Software modifications include the additional controllability of tunnel condition settings (i.e., Mach number, stagnation pressure, stagnation temperature, and dewpoint temperature) to the model attitude control system. Branches within the ATS software for Mach number control, that is, locating the sliding block nozzle and the second minimum for various Mach number settings, exist and await incorporation once closed loop control has been implemented. Communication links between ATS and the tunnel control system will be instituted once these additional ATS operations are in place and confirmed operational. Hence, increased capabilities of ATS are now in place and the first phase towards implementing the MDOE test option is complete. In it's present state, the MDOE test option provides improved user friendliness as opposed to the original OFAT controls option, makes pre-programmed test matrices of an increased number of parameters feasible and timed sequencing of those parameters possible. Also, this test option further decreases operator interaction and workload and permits additional ease of implementation of randomization of independent parameters like angle of attack, angle of sideslip, Mach number, and Reynolds number (i.e., pressure, temperature, and dewpoint control).

At this point there is still additional progress to be made, closed loop controls from ATS to field devices, feedback instrumentation, and motors are presently not in place or need connection and tuning. However, Phase II of this test option execution includes upgrades to these items as required, and establishment of communication links from ATS to the tunnel control system. A WTE re-investment project proposed to address these improvements has been approved and groundwork for this activity is projected to begin in spring 2001. Following culmination of this activity and a follow-on CoF project to implement additional control system upgrades for tunnel mode changes and further automated upgrades to manual operations, the entire MDOE test option for UPWT will be fully developed.

A detailed discussion of the MDOE method is presented in DeLoach, 2000. In addition to the MDOE process and its application to reduction of wind tunnel testing time other test cycle time reduction initiatives within the WTE are presented in Kegelman, 1999.

Enhanced Communication Capabilities for Test Coordination and Planning

A significant web-based communications capability is currently under development by a number of individuals within the Data Acquisition and Information Management Branch, Advanced Measurement and Diagnostics Branch, Data Analysis and Imaging Branch, Research Facilities Branch, and Systems Engineering and Control Branch and is called aeroCOMPASS. AeroCOMPASS is a new tool being matured under the auspices of the LaRC MERCATOR team. MERCATOR is an acronym for Managed Environment for a Reliable Communication Architecture to Organize Research. The charter for the MERCATOR team is to apply information technology to experimental test-related processes for the national research community.

The primary objective of aeroCOMPASS is to provide a common user interface to model, test, facility, research, project scheduling, and archival information. This approach integrates applicable existing technologies developed by various organizations into the aeroCOMPASS environment and provides a centralized location for accessing links to information and tools related to all aspects of the testing process. It is designed to eliminate the need for multiple-entry of the same information. Some items incorporated into aeroCOMPASS include: (1) wind tunnel data quality assurance tools, methodology, and facility participation information, (2) wind tunnel test simulators for estimating test durations, (3) test process management tools to monitor and participate in collaborative research projects from model design through data archival, (4) electronic logbooks/test notebooks via the use of approach to data management, archive, protection, and transmission (ADAPT) secure websites. It also includes numerous additional tools, processes, technical information archives, and emerging technology areas. Three phases are envisioned to bring aeroCOMPASS to completion and provide the user community with a navigational tool designed to provide a single portal to networked test-related functions (i.e., model, test, facility, research, project scheduling information) and databases (i.e., archival information).

At present, an aeroCOMPASS beta product delivery to the user community is scheduled for early 2001. A completion of Phase I activities and final production release is projected for spring 2001. A mid-2000 beta release of aeroCOMPASS has proved the underlying concept and provided a useful tool to a limited number of users thus, enhancing a number of research activities at Langley.

Future Facility Upgrades and Enhancements

The primary purpose of future upgrades for the UPWT will continue to address increased capability, reliability, and productivity. The UPWT has identified several future upgrades for the main compressor driveline planned to reduce auxiliary machine maintenance and improve run up time and online power control. A FY'03

CoF project is planned for replacement of the existing starting system with a solid state converter capable of bringing the existing synchronous motor up to line speed using variable frequency. Once the motor is operating at synchronous speed on the converter, a bypass contactor will close and the motor will operate normally. These system improvements eliminate the need for the induction motor, liquid rheostat, speed increaser gearbox, switchgear, and all associated controls. In order to maintain the power rating of the system, the new synchronous motor will be upgraded to 100,000 HP, which will be equal to the combined rating of the exiting synchronous and induction motors. Likewise, the project will eliminate the induction machine and gearbox, with all associated lubrication equipment and bearings. This streamlined version of the driveline will require less space and will strategically replace the oldest components of the main compressor lineup. The benefits to be realized are improved reliability, reduced maintenance, and ease of control and operation.

Another project will seek to provide Phase II upgrades to the Facility Automation System Controls and peripheral equipment. This project encompasses the additional control needed for complete tunnel automation. As part of this upgrade, additional closed loop control of configuration modes such as automated drop-flow configuration mode and shift "on-the-fly" configuration mode enhancements will be performed. ATS will acquire the additional control of block position and second minimum and a communications link will be provided from the tunnel control system for execution and optimization of the MDOE test option. Peripheral equipment modifications will include the updating of the Graphics Control Panel affecting control of tunnel configuration valves and systems like the cooling water system, vacuum system, air storage system, and assorted safety interlocks. These upgrades will enhance facility capability and reliability and provide for increased productivity.

Concluding Remarks

The Langley Unitary Plan Wind Tunnel (UPWT) is a closed-circuit continuous flow, supersonic, pressure tunnel possessing two test sections. This facility, originally designed and built in the late 1940's and early 1950's, as part of the United States Unitary Wind Tunnel Plan Act of 1949, provides a Mach number range from approximately 1.50 to 4.63 for a unit Reynolds number range of approximately 1.0×10^6 to 11.0×10^6 /ft. depending on Mach number. Construction of the UPWT was completed and the facility became operational in 1955. Throughout it's history the Langley Unitary Plan Wind Tunnel has contributed to developmental tests of virtually every supersonic military and industry aircraft, missile, and spacecraft to have become operational in the United States inventory. Research testing in the UPWT over these many years has provided for configuration assessment and optimization on the aerodynamic characteristics of numerous concepts. UPWT contributions include database development for a number of supersonic fighter aircraft and missiles, Space Shuttle Orbiter, National Supersonic Transports, High Speed Research, Personnel Launch Systems, Reusable Launch Vehicles (X-33, X-34, etc.), Crew Return Vehicle (X-38), Hyper-X (X-43), and many others. Typical tests include force and moment, surface pressure measurements, and flow visualization of on- and off-surface flowfield effects. Tests involving jet effects, global surface and off-body flow measurements, reaction control systems, hinge moments, dynamic stability, flowfield surveys, supersonic flutter, sonic boom, missiles, store drag, and heat transfer are also performed.

The present paper provides a brief overview of the NASA Langley Research Center's Unitary Plan Wind Tunnel operational capabilities and testing techniques. Recently performed facility productivity and efficiency upgrade initiatives through facility automation are presented. A limited number of configuration testing examples are reviewed which provide a discussion of UPWT facility utilization and synergism of Langley facilities for performing configuration screening and/or configuration aerodynamic databook development in support of various national programs. Several new and maturing thrusts presently underway that includes systematic efforts to provide credible assessment for data quality assurance, modifications to the new automation control system for increased compatibility with the Modern Design Of Experiments (MDOE) testing methodology, and process improvements for better test coordination, planning, and execution are discussed. The UPWT provides an excellent capability for parametric aerodynamic and specialized testing studies required in the early design and assessment stages of proposed advanced aerospace vehicles or for development of benchmarking databases as required for future national programs, such as 2[nd] and 3[rd] Generation Reusable Launch Vehicle.

Acknowledgments

The author wishes to acknowledge the contributions of Messrs. G. E. Erickson, F. J. Wilcox Jr., D. S. Shaw, and G. L. Humphreys, Research Facilities Branch; M. R. Rhode, W. C. Woods, and C. G. Miller, Aerothermodynamics Branch; R. DeLoach, Instrument Systems Development Branch; R. W. Ross, Data Acquisition and Information Management Branch; K. M. Gough, Data Analysis and Imaging Branch; G. H. Sydnor, Electrical and Electronic Systems Branch; and K. E. Wurster, Vehicle Analysis Branch, for their technical advice in the preparation of this paper.

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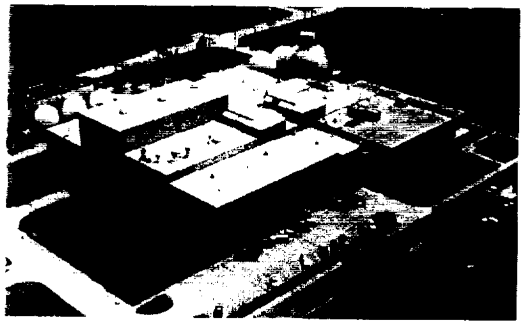


Fig. 1 - Aerial photograph of the NASA Langley Research Center Unitary Plan Wind Tunnel (UPWT).

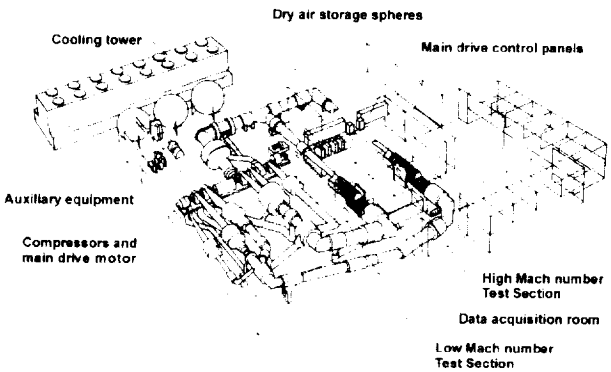
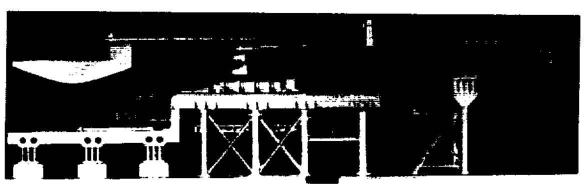
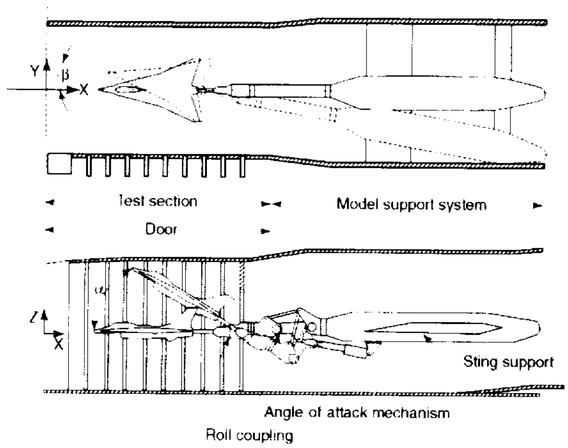


Fig. 2 - Schematic of the NASA Langley Research Center Unitary Plan Wind Tunnel (UPWT).

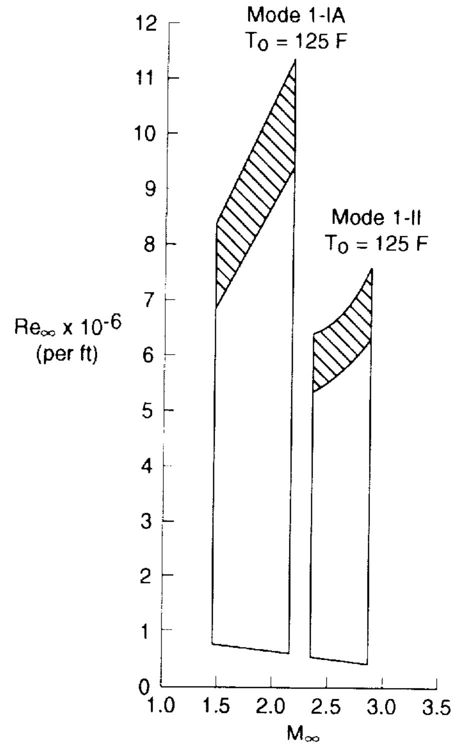


(a) Asymmetric sliding nozzle block.

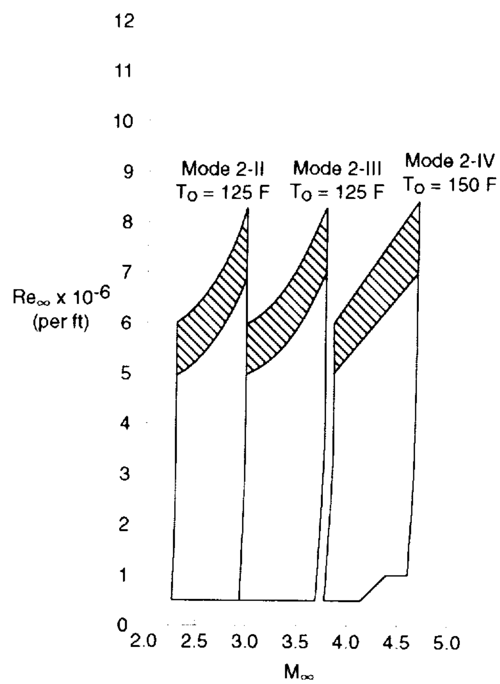


(b) Support system and test section layout.

Fig. 3 - Model of UPWT sliding nozzle block and schematic of test section area.

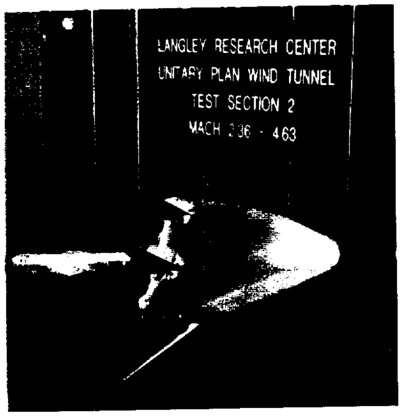


(a) Test Section #1

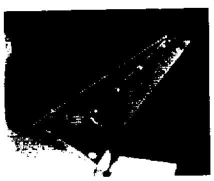


(b) Test Section #2.

Fig. 4 - Operating characteristics of the Langley Unitary Plan Wind Tunnel (UPWT); taken from Jackson et al, 1981. (Cross hatched area indicates regions of limited operations due to drive motor overload conditions.)



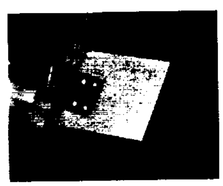
(a) 2%-scale "loads" model.



Canted Fin

Vertical Fin

Rudder



Body Flap

Elevons

(b) Strain-gauged components .

Fig. 5 - X-33 "loads" model installed in UPWT Test Section 2.

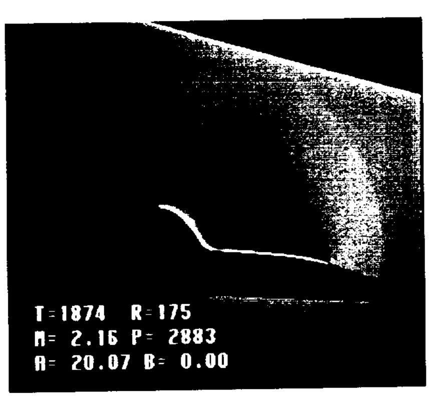


Fig. 6 - Vapor screen flow visualization image of a general research fighter aircraft.

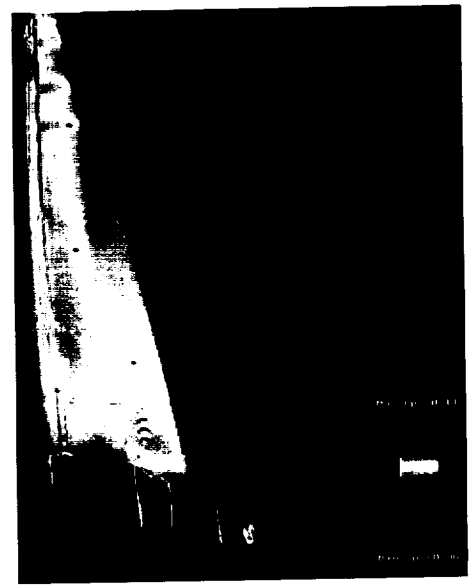


Fig. 7 - PSP image of arrow wing model at $M = 1.65$, $\alpha = 6°$, and $Re/ft = 3 \times 10^6$.

Fig. 8 - Sonic boom model shock wave image at Mach=2.0.

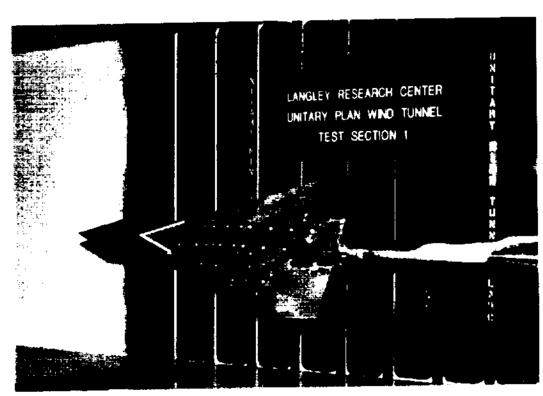


Fig. 9 - General research fighter model with 65 deg. cropped delta wing, LEX, and twin vertical fins.

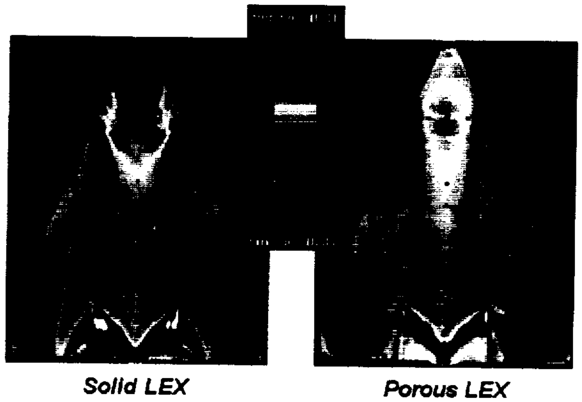


Fig. 10- Effect of LEX porosity on PSP intensity field images for fighter model at M=1.6 and α=8° with wing mounted vertical fins.

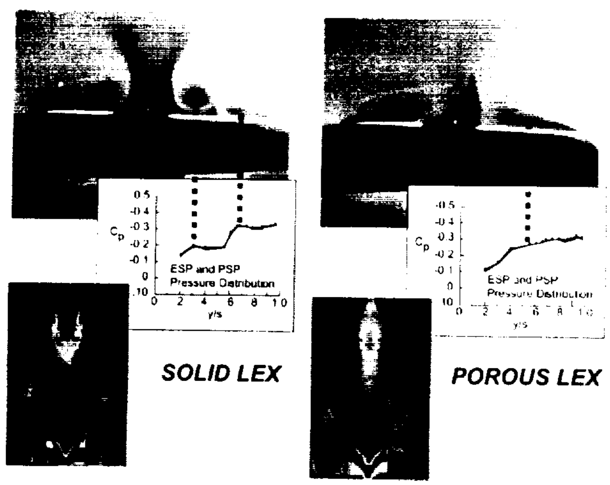


Fig. 11 - Correlation of measurement techniques for a general research fighter at Mach=1.6, α=8°, x/c=0.80.

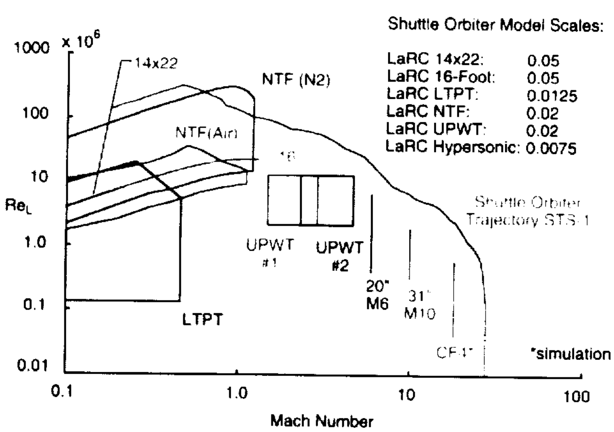
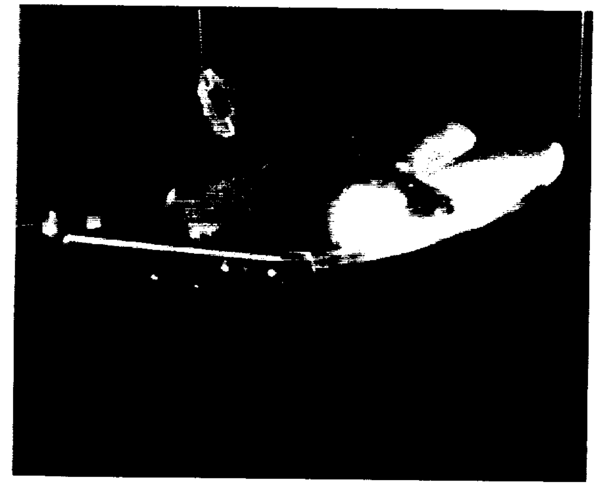
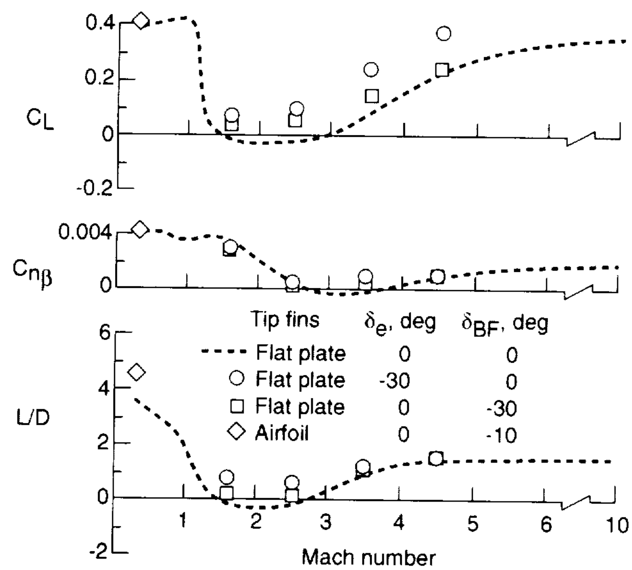


Fig. 12 - Operational characteristics for a number of Langley's test facilities from subsonic through hypersonic test conditions.

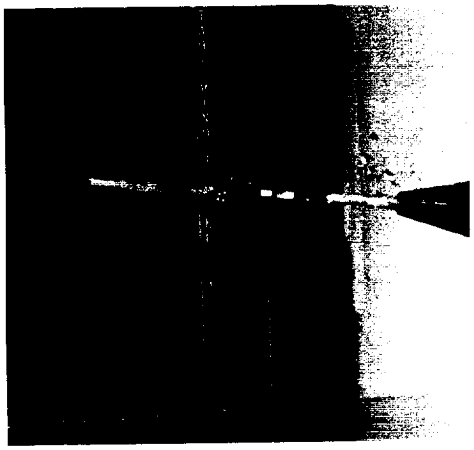


(a) HL-20 model mounted in the LaRC Unitary Plan Wind Tunnel.

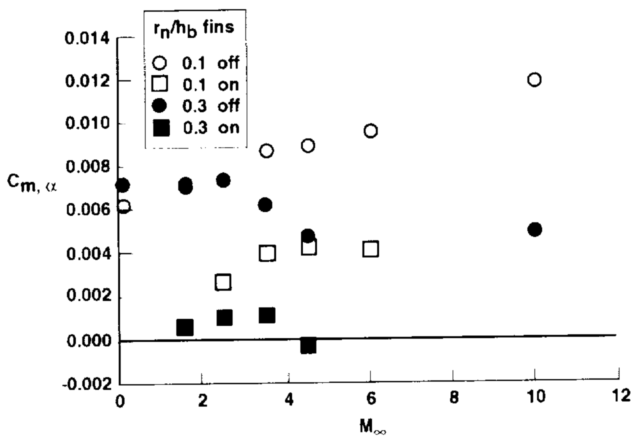


(b) Summary of trimmed aerodynamic characteristics over the Mach range (taken from Ware, et al, 1993).

Fig. 13 - Cross facility testing of the HL-20 configuration in Langley wind tunnels.

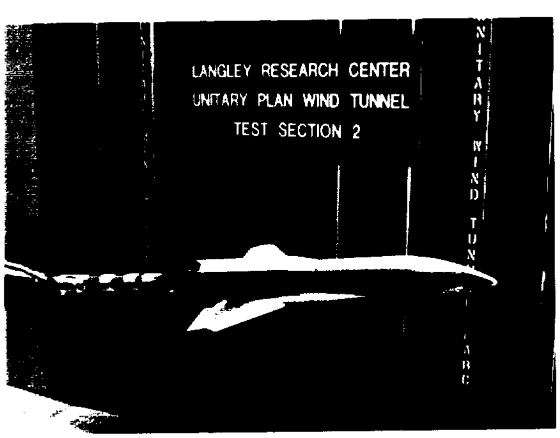


(a) VTVL model mounted in the LaRC Unitary Plan Wind Tunnel.

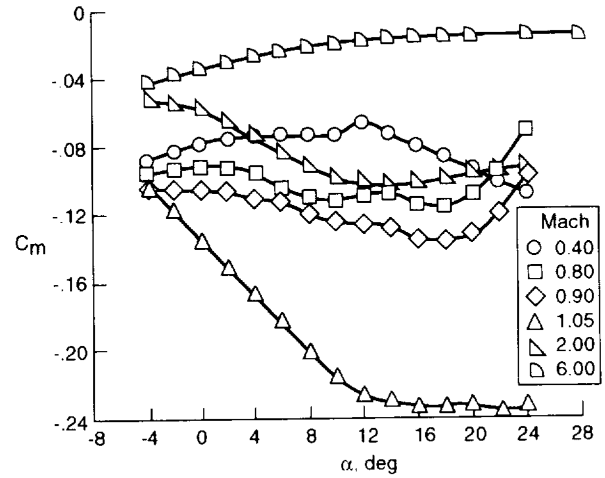


(b) Effect of Mach number, landing gear covers, and nose bluntness on VTVL pitch curve slope (taken from Woods et al, 1995).

Fig. 14 - Cross facility tests of a vertical take-off/vertical landing (VTVL) configuration using a single scale model.



(a) 0.033-scale model in the LaRC UPWT.



(b) Pitching-moment characteristics as a function of Mach number (taken from Brauckmann, 1999).

Fig. 15 - Cross facility testing of the X-34 configuration in Langley wind tunnels.

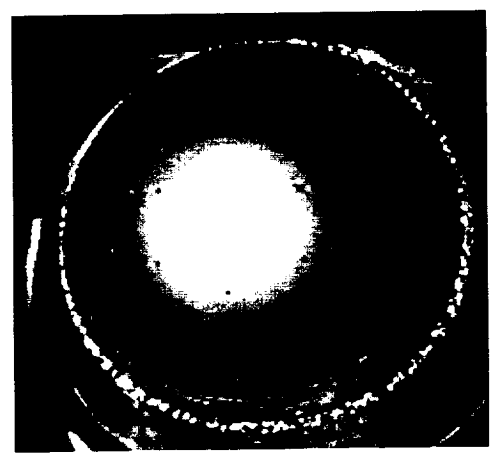


Fig. 16 - Close-up image of instrumented nose cap for FADS calibration on a 2%-scale X-33 model.

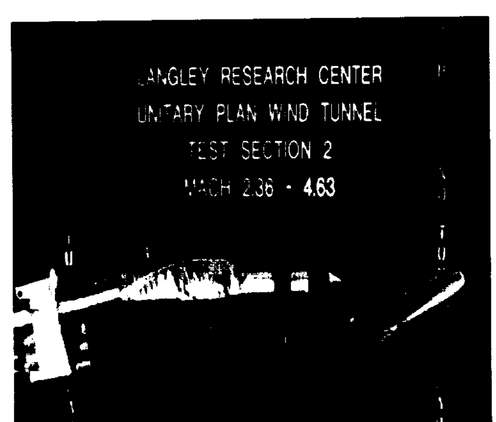
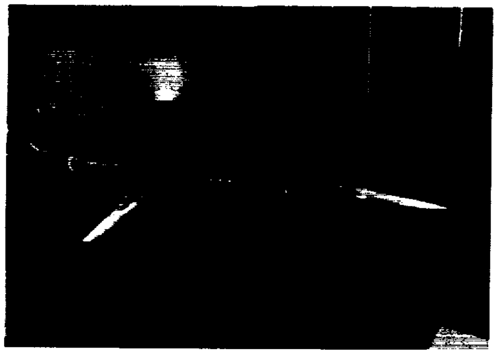
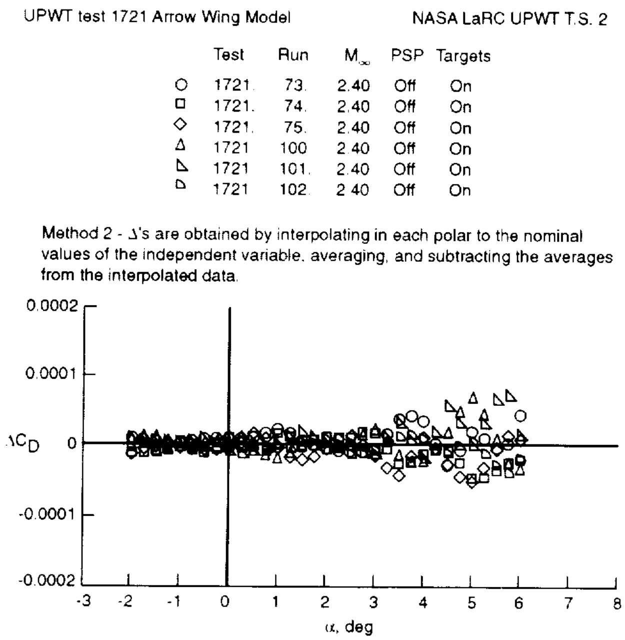


Fig. 17 - 1%-scale X-33 RCS model installed in UPWT Test Section 2.



(a) Interim check standard model for UPWT



(b) Data scatter plot for drag coefficient at Mach=2.4 (beginning to end of test; taken from Erickson, 2000).

Fig. 18 - Check standard model testing in the LaRC UPWT.

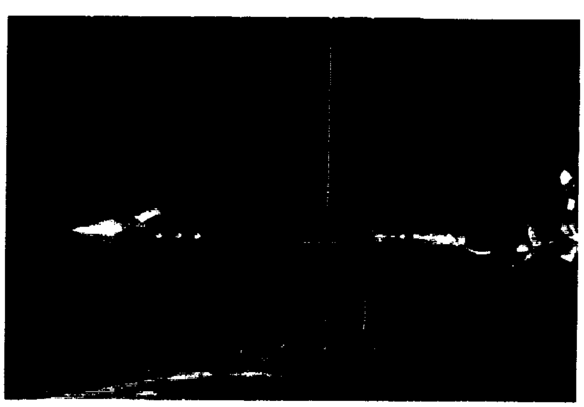


Fig. 19 - New check standard general research fighter model installed in the LaRC UPWT.

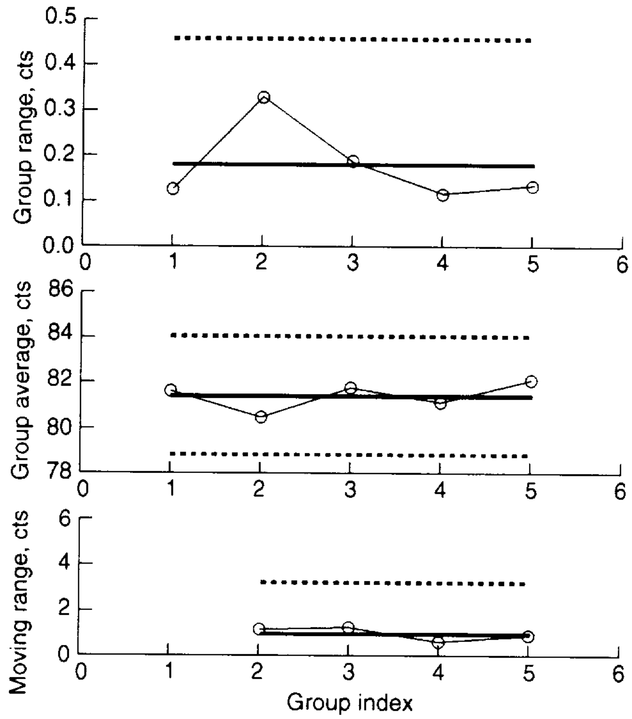


Fig. 20 - 3-way charts for interim check standard model in Test Section 2 of the LaRC UPWT; axial force coefficient, $M_\infty = 2.4$, $\alpha = 2.5$ deg. (1 ct = 0.0001).

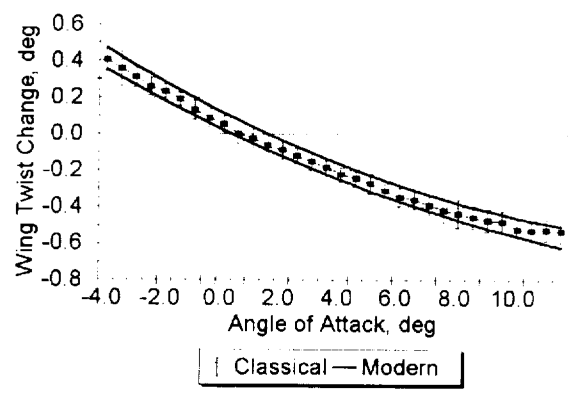


Fig. 21 - Wing twist obtained using OFAT and MDOE testing techniques (taken from Erickson, 2000).