Pressure-Sensitive Paint and Video Model Deformation Systems at the NASA Langley Unitary Plan Wind Tunnel

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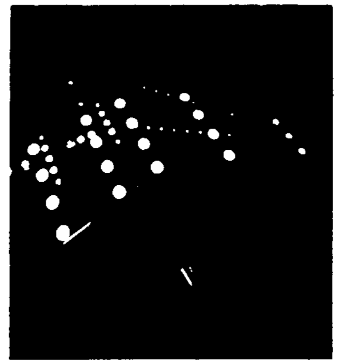
Pressure-sensitive paint (PSP) and video model deformation (VMD) systems have been installed in the Unitary Plan Wind Tunnel at the NASA Langley Research Center to support the supersonic wind tunnel testing requirements of the High Speed Research (HSR) program. The PSP and VMD systems have been operational since early 1996 and provide the capabilities of measuring global surface static pressures and wing local twist angles and deflections (bending). These techniques have been successfully applied to several HSR wind tunnel models for wide ranges of the Mach number, Reynolds number, and angle of attack. A review of the UPWT PSP and VMD systems is provided, and representative results obtained on selected HSR models are shown. A promising technique to streamline the wind tunnel testing process, Modern Experimental Design, is also discussed in conjunction with recently-completed wing deformation measurements at UPWT.

Presentation Overview



- **Review of UPWT PSP system and selected results obtained on HSR models**
- **Review of UPWT VMD system and selected results from recently-concluded HSR testing**
- **Discussion of a Modern Experimental Design method for improved wind tunnel productivity**
  - **-- recently applied at UPWT in conjunction with the VMD system to predict HSR model deformation**

A comprehensive facility enhancement program is underway at the NASA Langley Research Center Unitary Plan Wind Tunnel to provide state-of-the-art test techniques to support the supersonic testing requirements of the High-Speed Research program. This paper provides a review of the UPWT pressure-sensitive paint system for global surface static pressure measurements and the UPWT video model deformation system to measure wing local twist and deflections. In an effort to improve wind tunnel productivity, a Modern Experimental Design technique was used in parallel with the model deformation system to determine its effectiveness in predicting wing twist at supersonic speeds. Representative results obtained with the PSP, VMD, and Modern Experimental Design techniques in recent HSR wind tunnel model testing at UPWT are presented.

PSP and VMD Systems at UPWT

- **PSP and VMD systems established at UPWT in 1996 to support HSR experimental programs**
- **Strong cooperative efforts involving Aero-Gas Dynamics Division and Experimental Testing Technology Division (ETTD)**
- **PSP system evolved from previous installation in the NASA Langley 8-Foot Transonic Pressure Tunnel in 1994 in cooperation with NASA Ames and ETTD**
- **VMD systems established at the National Transonic Facility and Transonic Dynamics Tunnel in 1994 provided foundation for UPWT installation**
- **PSP and VMD systems are now operated by UPWT personnel after extensive training with ETTD (setup, operation, image acquisition and processing, and data analysis and plotting)**

Cooperative efforts involving personnel from the NASA Langley Aero-Gas Dynamics Division and the Experimental Testing Technology Division have led to the establishment of PSP and VMD deformation systems at UPWT. A PSP system previously installed in the NASA Langley 8-Foot Transonic Pressure Tunnel was upgraded and installed in UPWT in early 1996. This system was modeled after a similar setup currently in use at the NASA Ames Research Center. The VMD systems established by ETTD at the National Transonic Facility and the Transonic Dynamics Facility served as models for the UPWT installation, which was initiated in 1996. Experience gained from several HSR-sponsored tests has provided resident expertise at UPWT in all aspects of the PSP and VMD systems.

UPWT Description

- Closed-circuit, continuous-flow, variable-density tunnel
- Two 4-ft by 4-ft test sections
- "Low Mach" test section has a design Mach number range from 1.5 to 2.9
- "High Mach" test section has a design Mach number range from 2.3 to 4.6
- Both test sections use asymmetric sliding-block nozzles that allow continous variation in Mach number
- Maximum Reynolds number/foot varies from 6×10^6 to 11×10^6, depending on Mach number

The NASA Langley UPWT is being extensively used in the HSR program to provide aerodynamic performance and stability and control characteristics at supersonic speeds. The ranges of Mach number and Reynolds number, the control of the dewpoint and stagnation temperature, the optical access to the test section, and the benign environment for the installation of digital and video imaging equipment are factors that render UPWT well-suited to the application of PSP and VMD techniques. The PSP and VMD systems are portable between the "low Mach" and "high Mach" number test sections. In addition, the present facility scheduling features one "active" test section while the "idle" test section is available for PSP and VMD system set-up, check-out, and test technique enhancements.

UPWT PSP System

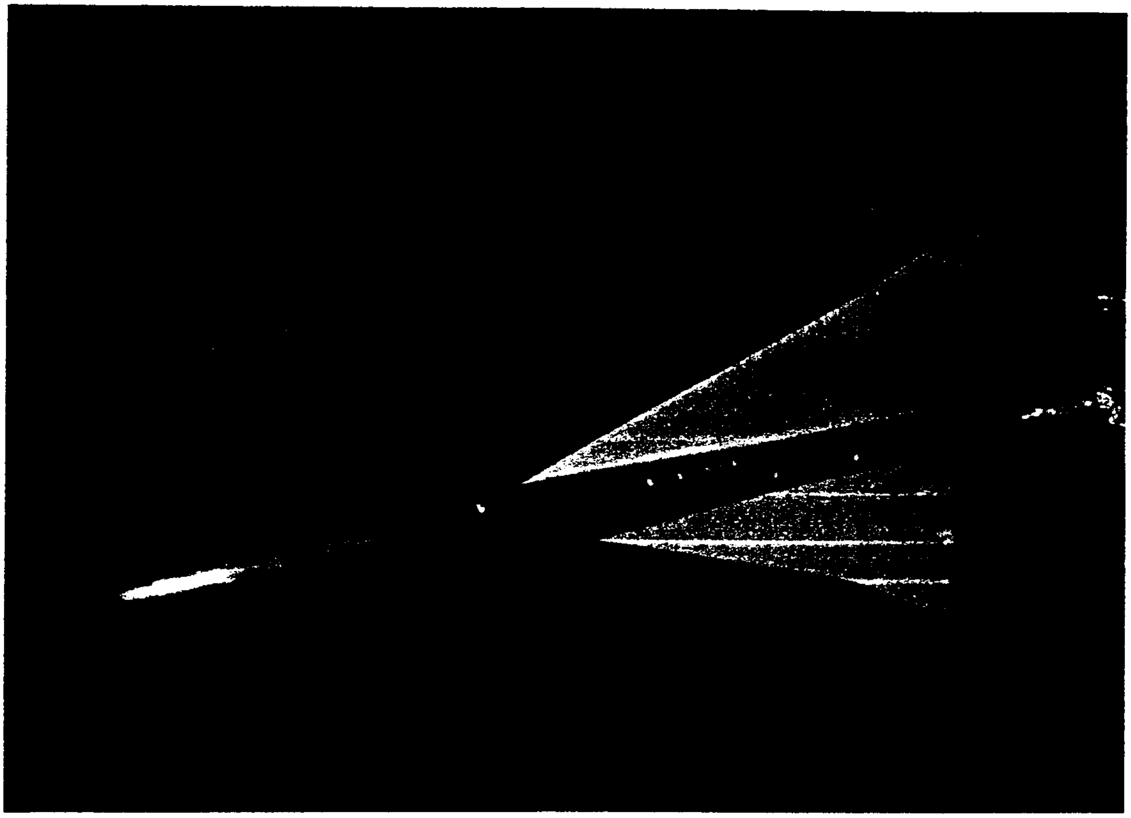
- Method is based on oxygen sensitivity of photoluminescent material in the form of a "paint" (University of Washington formulation)
- PSP sprayed onto model surface after application of white undercoat
- Purge air is applied through model surface pressure orifices during painting process via electronic pressure scanner modules installed in the wind tunnel model
- Registration marks applied to model using overlay template
- PSP excitation source is 250-W lamps that emit ultraviolet light in a broadband centered around 360 nm and a cutoff filter to block emission in the visible wavelengths
- All other illumination sources are eliminated by installing "light-tight" enclosures on both sides of the wind tunnel test section

The UPWT PSP technique is based on a system developed by the NASA Ames Research Center and the University of Washington. The photoluminescent paint chemistries developed by the University of Washington have been used in all of the NASA Langley UPWT PSP tests and have proved to be very robust for the supersonic experiments. Approximately one shift is required to the application and curing of the white base and PSP coatings. Specially modified ESP scanners, when operated in a purge mode, route air through the wing surface pressure lines to prevent the paint from clogging the orifices. Registration marks are applied to the painted surfaces using an overlay template and a black marking pen. The marks are tyically 0..125 to 0.188 inches in diameter and are positioned along the edges of the model and at selected other locations on the wing. UV lamps are mounted to the webbing of the the test section side wall to provide a continuous illumination source. Manual shutters are used to block the UV light between runs. The large image areas that are typically mapped on HSR models requires at least two UV lamps. Photodegradation of the PSP is a concern because of the proximity of the UV light source to the model (approximately 2 feet), so double and triple filters are applied to the lamps to reduce the UV intensity at the model. A hand-held digital radiometer is used to measure the effectiveness of the UV lamp positioning and filtering arrangements. Wooden enclosures have been built that are bolted/clamped to the test section side walls to eliminate all extraneous light sources.

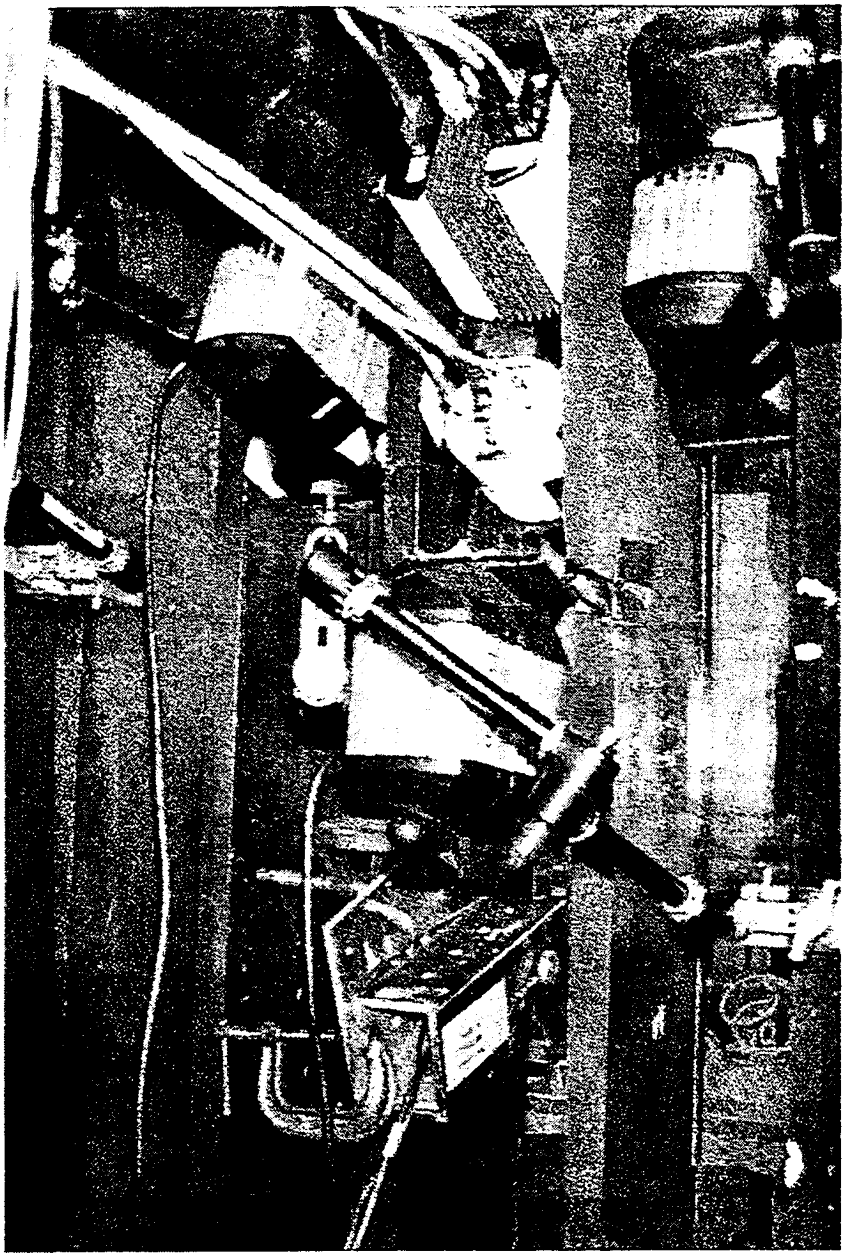
UPWT PSP System (continued)

- **PSP imaging is conducted using 2 scientific-grade, cooled CCD digital cameras (12-bit and 14-bit intensity resolution, 512x512 and 1024x1024 spatial resolution) installed in the "webbing" of the test section side wall**
- **Optical filters are installed on the camera lenses to permit the passage of the luminescence emission wavelengths while blocking other wavelengths**
- **Model is rolled 90^0 for best optical access and the model pitch angle is varied using the support system yaw mechanism**
- **Camera integration time and image acquisition are controlled by host computers located in the UPWT Data Room, about 125 feet from the camera positions**

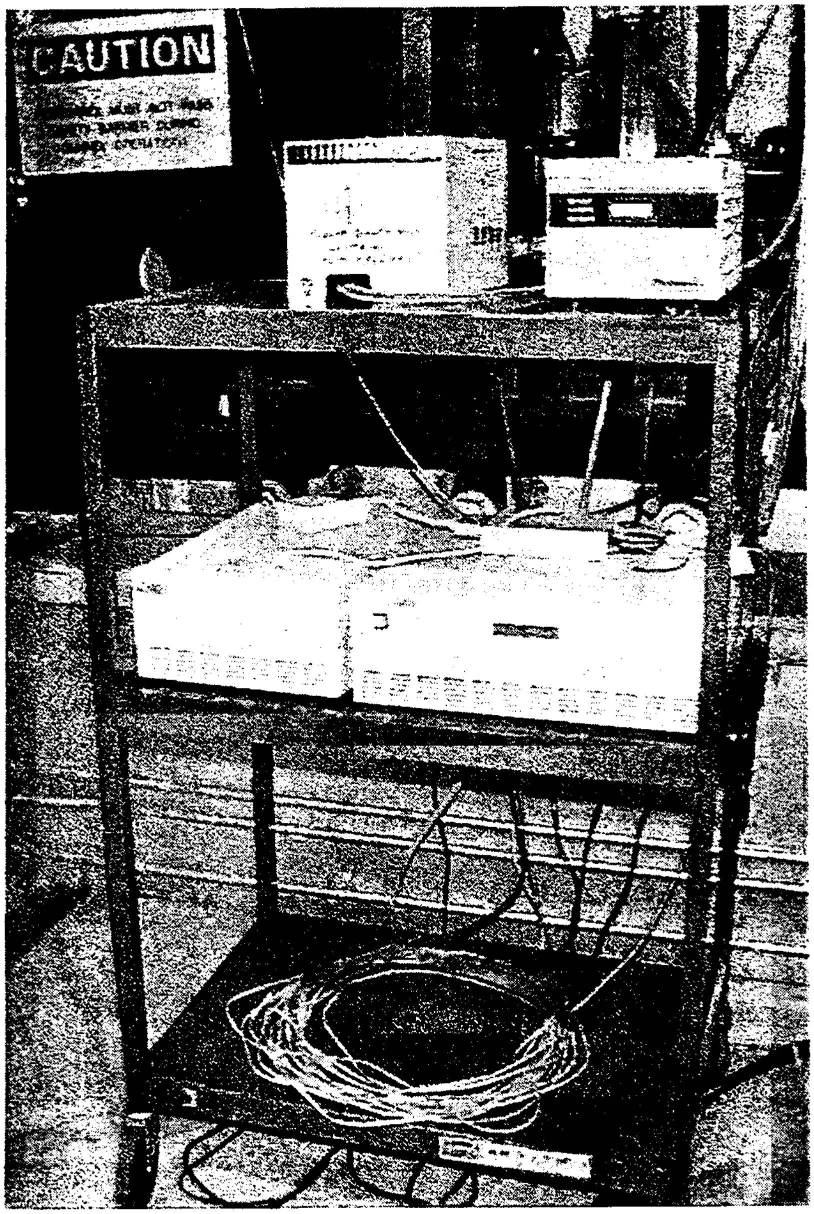
The high CCD performance, low noise, linear response, and good signal-to-noise ratio of scientific-grade digital cameras provide high-precision, quantitative light measurements. Two digital cameras are available at UPWT for PSP image acquisition. In a typical installation, both cameras are mounted inside the webbing of the test section side wall with lenses that are selected to provide a detailed view of an area of particular interest on the model and a global view of the wing surface. Special optical filters are mounted to the front of each lens so that the camera detects only the luminescence emission spectra. Optical access to the test section is available through the schlieren windows in the side walls, so the model is rolled 90° to be roughly orthogonal to the cameras. Variation in the model pitch angle is obtained using a mechanized yaw mechanism. The camera exposure, or integration, time and image acquisition are remotely controlled via a Windows 95-based PC and a UNIX-based workstation that are located in the UPWT Data Room. The integration times are selected to provide high image intensity while avoiding local saturation. Typical integration times are 1 to 1.5 seconds. PSP imaging has not been compromised by the relatively minor model dynamics that are encountered at the supersonic speeds.



This photograph shows a 1.675%-scale HSR arrow wing model installed in UPWT test section 1. The model is rolled -90^0 for this photograph, although the model was rolled in the opposite direction for the testing. The right (upper) wing surface is coated with pressure-sensitive paint, while the left (lower) wing features an application of temperature-sensitive paint.



The photograph shows a close-up view of a PSP hardware installation in the webbing of UPWT test section 2. Two scientific-grade CCD digital cameras, one standard video CCD camera, and three 250W UV lamps are installed using articulated mounting arms or C-clamps. The webbing provides a stable, virtually vibration-free mounting surface for the PSP imagers and light sources.

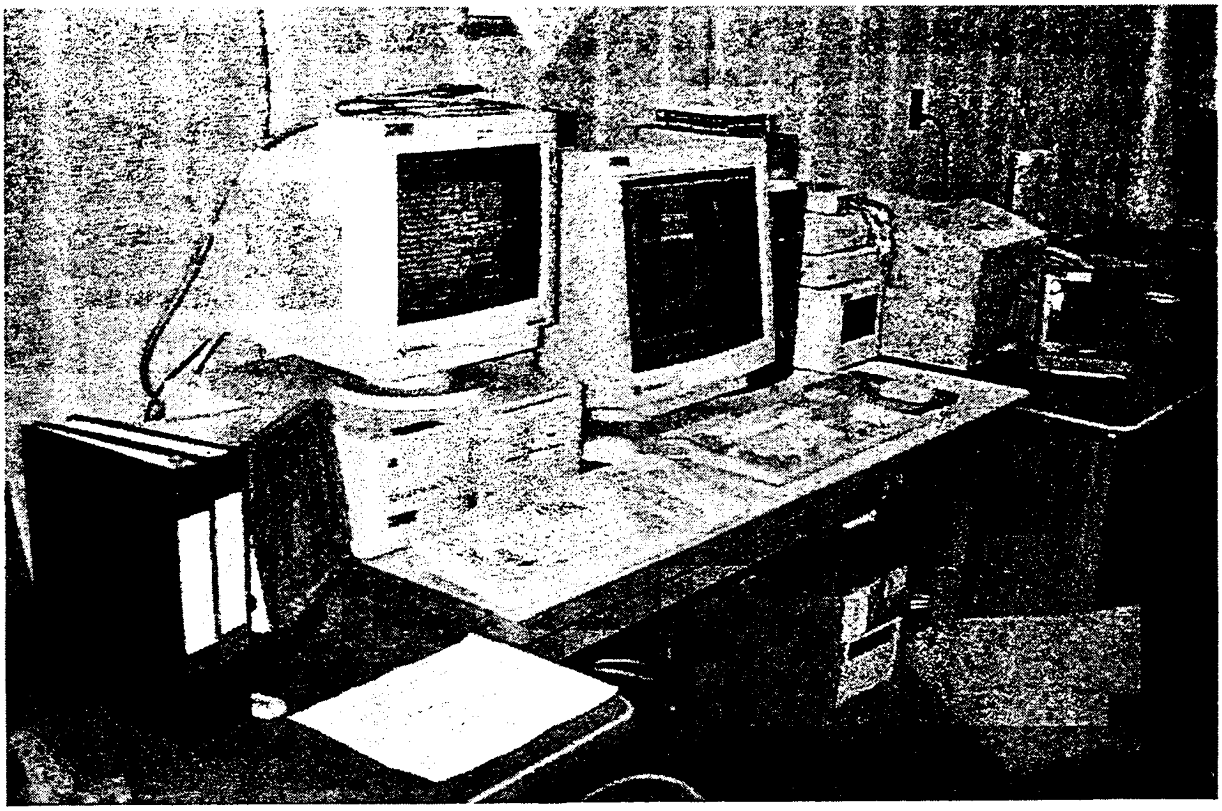


The PSP digital camera electronic control units and chiller units are shown in this figure. Excess length of a 200-foot fiber optic cable is shown at the bottom of the mobile cart, which is positioned adjacent to the test section.

UPWT PSP System (concluded)

- Personal computer controls the 14-bit camera via a proprietary interface card and electronics cable, while a UNIX-based workstation controls the 12-bit camera using a separate interface and a fiber optic-based SCSI link
- Video camera with optical filter provides real-time PSP response
- Wind-off and wind-on images are processed on the UNIX machine using the NASA Ames-developed "paintcp" software package, which performs the image ratio, registration, and paint calibration operations
- PSP is calibrated via an "in-situ" method using surface static pressures obtained from discrete orifices on the model surface connected to internally-mounted ESP scanners
- Image processing, analysis, and plotting are performed on-site and results posted on WWW site established for each UPWT test

The 14-bit digital camera with 512x512 pixel array is controlled by a personal computer and camera interface card. A camera electronics cable extends from the interface card to an electronics control unit and camera chiller unit assembly located adjacent to the test section. The 12-bit digital camera with 1024x1024 pixel array is controlled by a high-end workstation that features a fiber optic-based SCSI bus extender from the workstation to the camera control unit/chiller unit assembly, also positioned in proximity to the test section. Electronics cables and fiber optics cables are permanently routed from the Data Room to both test sections. A separate video CCD camera with optical filter is mounted to the test section webbing to provide real-time display and recording of the paint response, which can include the footprints, or signatures, of shock waves and vortices. An extensive disk array has been assembled to accommodate the image storage requirements of PSP testing. All images are transferred to the workstation, where the image ratioing, image registration, and PSP calibrations are performed using a software package developed by NASA Ames Research Center. An "in-situ" calibration is performed whereby the paint is calibrated using the static pressures measured at discrete locations with internally-mounted pressure scanners. All image processing operations and data analysis and plotting are done on-site. World Wide Web sites are typically established for each UPWT test to allow posting of the processed PSP images.



The host computers that control the two PSP digital cameras are shown in the photograph above. The PC (Windows 95 OS) and UNIX workstation are situated side-by-side along with high-capacity disk drives and color postscript printer. Additional magneto-optical hard drives and recordable CD drives have recently been acquired to augment the UPWT PSP system.

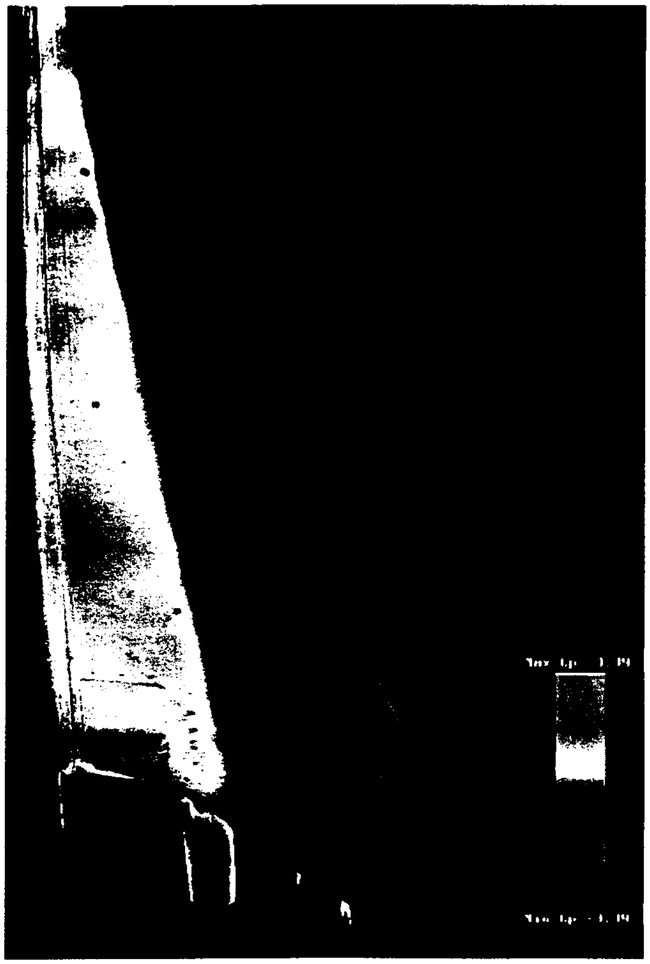
UPWT PSP Applications to Date

- 1.675%-scale HSR arrow wing model
- 1.675%-scale HSR TCA 2a model
- Test sections 1 and 2
- M=1.6 to 2.7, Re/ft=3, 4 million
- $\alpha = -2^o$ to 8^o
- Attached flow, separated (vortex) flow, shock waves

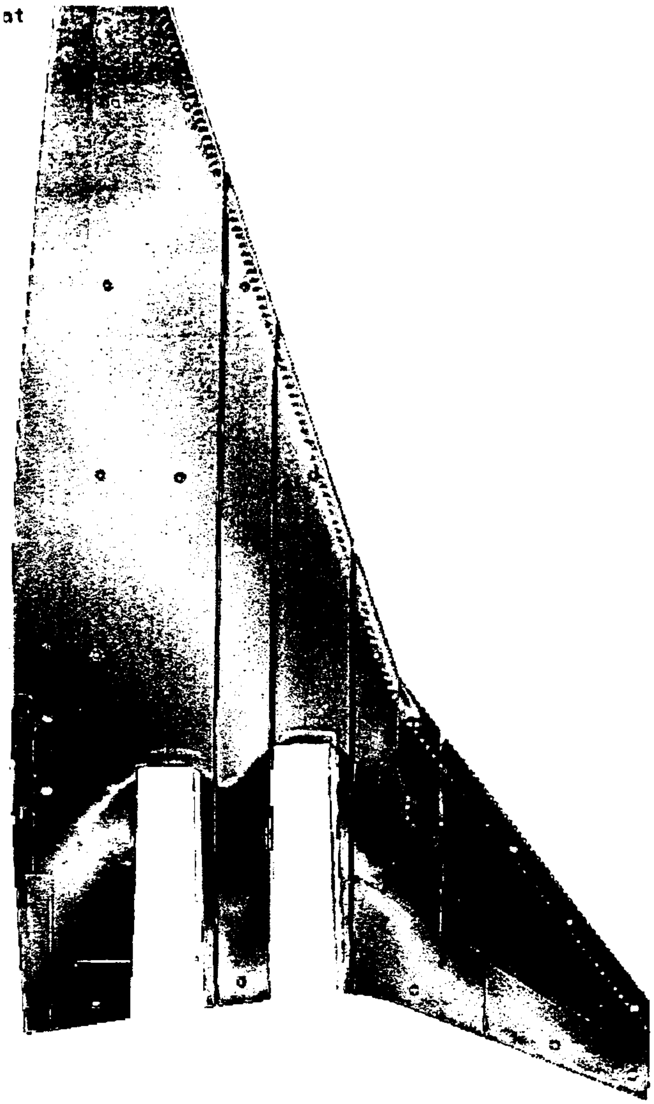
The UPWT PSP system has been applied to several HSR models, including a 1.675%-scale HSR arrow wing model in test sections 1 and 2 and a 1.675%-scale model of the HSR TCA2a model in test section 2. PSP results have been obtained for a wide range of Mach number and angle of attack that encompass flow regimes dominated by attached flow, vortices, and shock waves. Time required to set up the PSP system and acquire all wind-on and wind-off images is approximately 2 shifts. Additional time is required at the outset of the wind tunnel entry to acquire flow angle corrections (upflow and sideflow) to provide accurate determination of the model angle of attack. Runs are also made of the unpainted model at the same test conditions to quantify any obtrusive effects of the paint thickness on the wing surfaces.

Arrow Wing PSP Image at M=1.65, α=8°

UPWT Test 1836 Re/ft = $3(10^6)$ June 1996

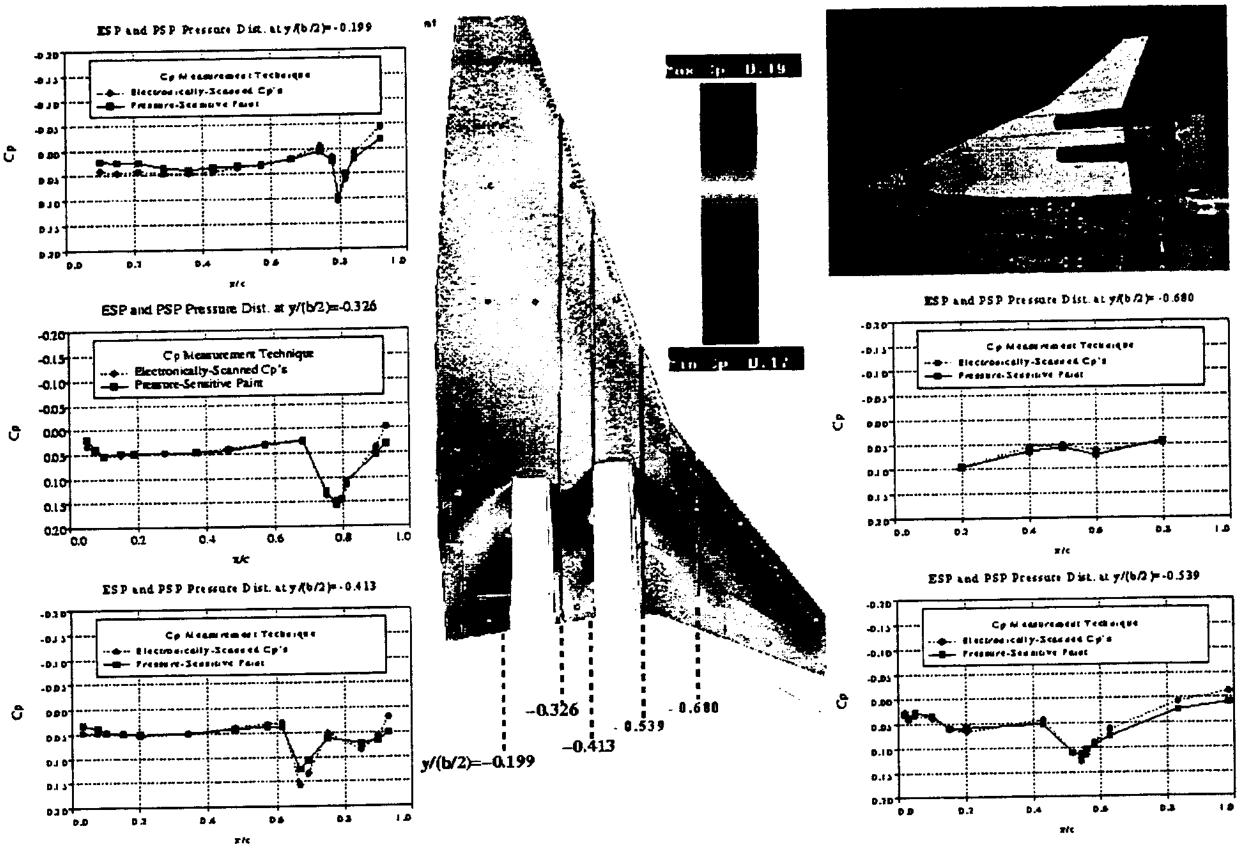


The photograph shown above is a false-colored, ratioed and registered image of the wing upper surface pressure field on a 1.675%-scale model of an HSR arrow wing configuration. The test conditions correspond to a free-stream Mach number of 1.65, Reynolds number per foot of $3(10^6)$, and angle of attack of 8°. Free-stream stagnation temperature is 125 °F. The PSP image clearly shows the signatures of leading-edge vortices that develop from the inboard and outboard wing regions. The inboard wing vortex passes over the outboard nacelles, and the effect of the vortex passage can be correlated with the nacelle base pressure measurements. The paint was calibrated using pressure measurements obtained at discrete ports with two ESP modules. This test was conducted in June 1996 and was the first application of the UPWT PSP system in UPWT test section 1.



A processed PSP image of the wing lower surface on a 1.675%-scale model of the HSR TCA 2a in UPWT test section 2 is shown above. The test conditions correspond to a Mach number of 2.4, Re/ft = $4(10^6)$, T_{stag}=125^0, and α = 3.5^0. The inboard and outboard nacelles were installed for this run, but were painted flat black to eliminate the effect of reflected light from the sides of the nacelles on to the wing surface. Of particular interest in this application was the character of the interacting shock waves developed by the nacelle diverters. Reflected shocks from the diverters are also discernible in the original image and in the PSP-derived static pressure distributions. Several streamwise rows of wing lower surface static pressure orifices were plumbed to an ESP module without the purge air capability. As a result, thin strips of masking tape were applied to these rows during the painting process. These unpainted strips are visible in the image above. The in-situ paint calibration required the selection of pixel locations outside of these regions.

Pressure- Sensitive Paint Results on HSR TCA 2 Wing Lower Surface
M=2.40 α=3.5° Re/ft=4(10⁶) UPWT Test 1671 (PXL Camera)

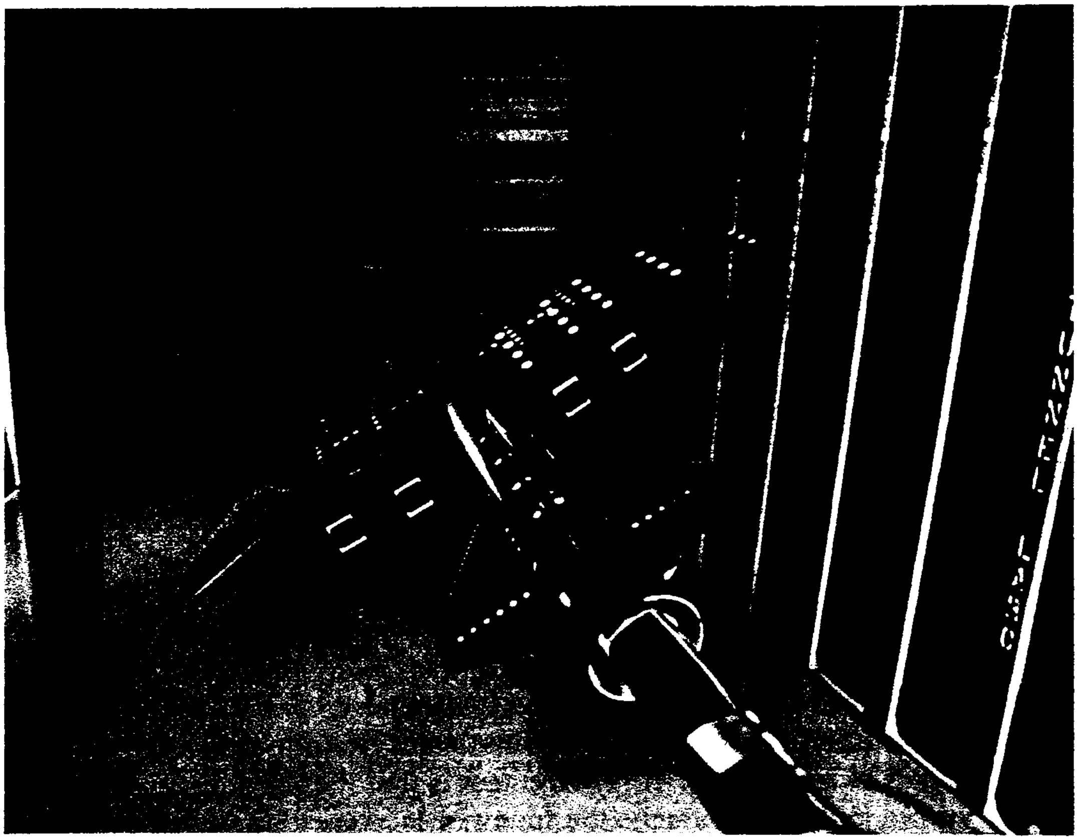


This composite plot compares the streamwise distributions of the wing lower surface static pressure coefficient obtained with the PSP technique and the electronically-scanned pressure modules at Mach=2.4, Re/ft=4(10^6), and α = 3.5^0 (same case as on previous page). The ratioed and registered PSP image and a model installation image are also included. The PSP and ESP pressure data compare very well, and the maximum difference in the coefficients obtained with the two methods is within approximately 5% of full-scale range of the ESP transducers . The abrupt pressure rise across the shocks is apparent in the first four pressure distribution plots. Note that the PSP data plots are restricted to values obtained at a single pixel in proximity to each pressure orifice. The advantage of the PSP method is that all image pixels are "pressure tap" locations, and the corresponding hundreds of thousands of pixels (depending on the camera resolution) can provide much higher resolution of the C_p distribution, particularly across the shock waves.

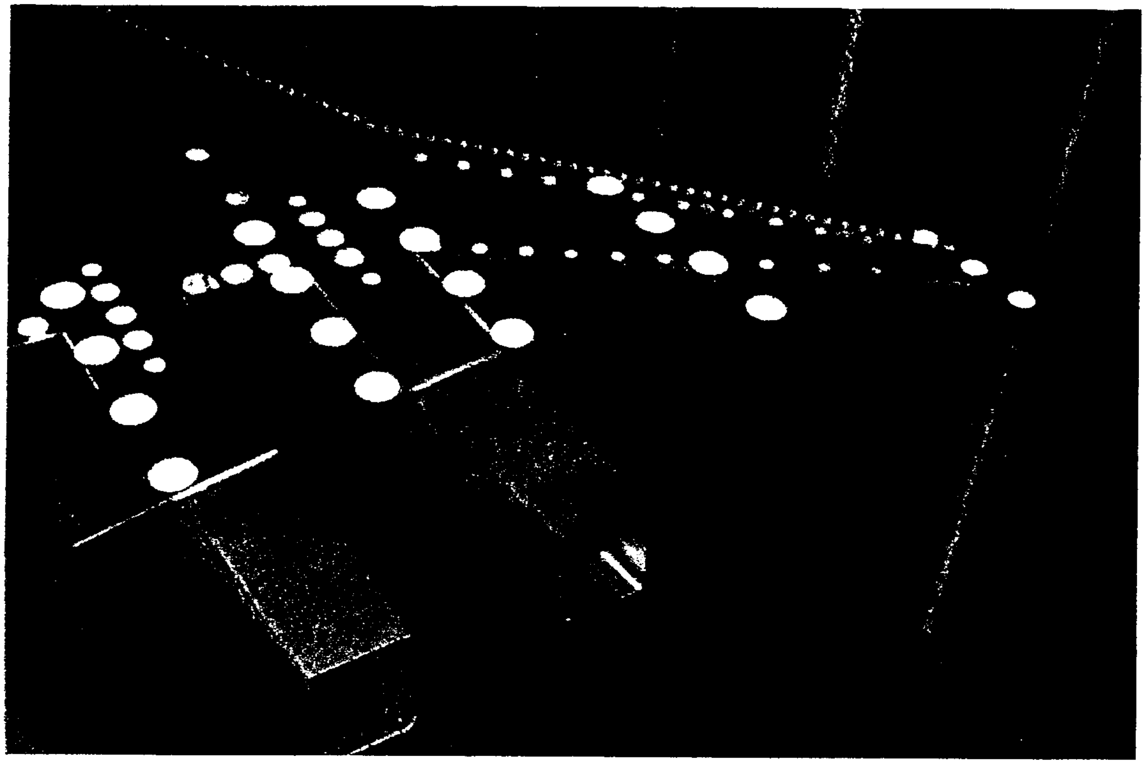
UPWT VMD System

- VMD technique is based on a single video camera photogrammetric determination of two-dimensional coordinates of wing targets with a known fixed third dimensional coordinate (spanwise location)
- Primary application of UPWT VMD system is to determine local wing twist, while secondary applications include wing deflection (bending) and model angle of attack measurements
- Retroreflective dots with adhesive backing are applied in several chordwise rows from the wing root to the wing tip to provide high-contrast targets
- Images are acquired using a standard RS-170 CCD video camera with 752 horizontal by 240 vertical pixel resolution
- Illumination source is a fiber optic-based ring light mounted to the front of the camera's 10 to 100mm focal length remote zoom lens

A unique aspect of the video model deformation system developed by NASA Langley ETTD is the photogrammetric determination of two-dimensional wing targets using a single video camera. A requirement is that the third dimensional coordinate be known and fixed, namely, the spanwise location of the targets. The primary application of the VMD system is to measure the wing local twist angle, although the wing deflection (bending) and model angle of attack measurements may be equally significant depending on the experimental objectives. Targets in the form of retroreflective dots with an adhesive backing are applied at precisely known locations in chordwise rows at several wing span stations. The inboard row of targets is placed in a region of the wing that may be considered rigid. This row serves as a reference to all other target rows and provides an "onboard" angle of attack measurement. The dots provide extremely high-contrast targets for image acquisition, and any glints or other undesired sources of high contrast on the model surface are eliminated by applying a thin coat of flat black paint to these regions (Note: This is not a standard practice at all facilities.) The thickness of the targets is somewhat instrusive and may cause drag coefficient increments of a few counts at the supersonic speeds; as a result, the VMD measurements are generally made in a separate run series in a manner similar to the PSP technique. A standard CCD video camera with characteristics that have been well-documented by ETTD is used to acquire images of the targeted region. Uniform illumination of the model is provided by a fiber optic-based ring light that easily attaches to the front of the camera's remote zoom lens.



The 1.5%-scale HSR TCA 20 model installed in UPWT test section 1 is shown in the above photograph, taken at the conclusion of a recent video model deformation experiment. The 5 chordwise rows of retroreflective targets are visible on the right wing upper surface.



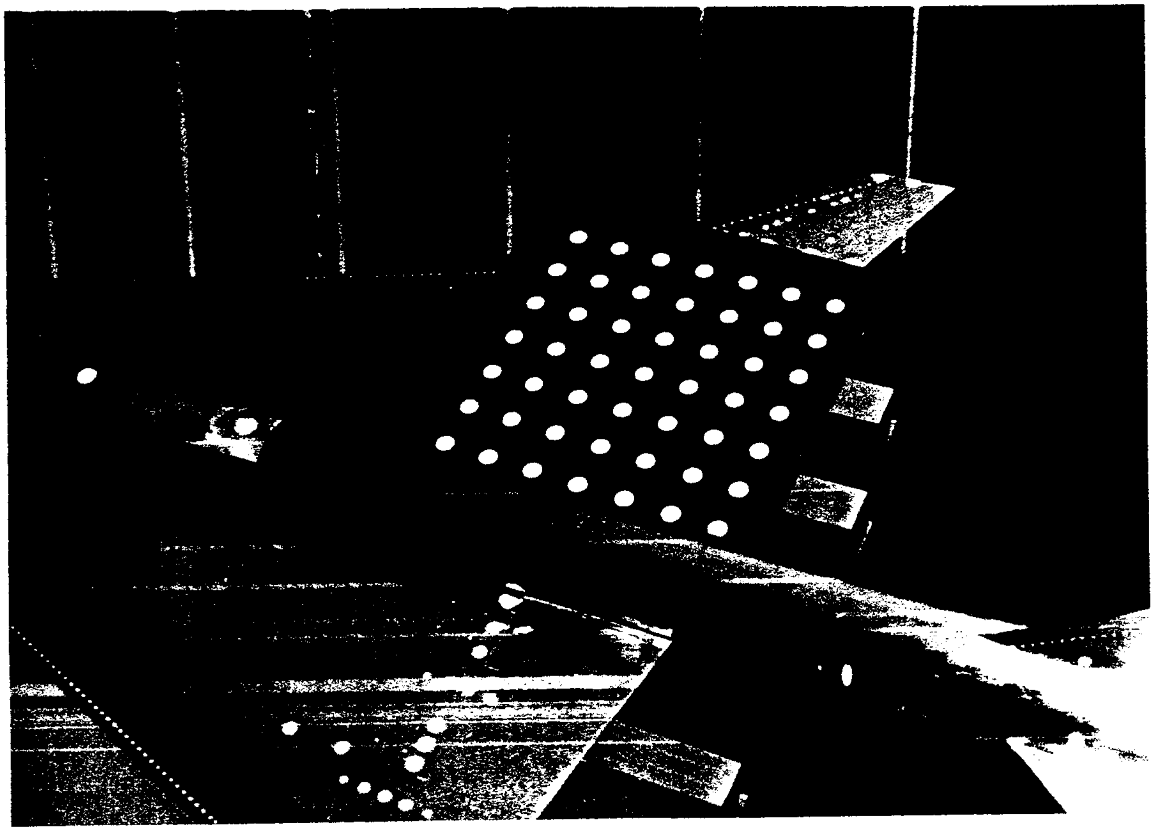
The figure above shows a close-up view of the right-hand wing upper surface on the 1.5%-scale HSR TCA model 20 installed in UPWT test section 1. Five rows of retroreflective targets are visible; the first four chordwise rows (starting from the wing root region) feature four 0.188-inch diameter targets while the fifth row (at the wing tip) has three 0.125-inch diameter targets. The wing twist and deflection measurements that are presented in following figures correspond to the row near the wing tip. Note that several smaller screw holes in the wing surface are filled with dental plaster, and these holes can be miscontrued in the photograph as VMD targets. These holes are not visible during the image acquisition process.

A close-up view of the VMD system camera installed in the webbing of the test section is shown in this photograph. The standard video CCD camera is mounted to the remote zoom lens which, in turn is bolted to an angle plate that is C-clamped to the webbing. The fiber optic link to the lens-mounted ring light is also discernible in the figure. Considerable care is required to ensure that that the focal length and camera position are not changed once the camera calibration is completed. The video signal from the camera is routed to the Data Room via an RG-59 cable to a video distribution amp and to the video framegrabber board in the PC image acquisition system. Set-up of the VMD camera equipment is very straightforward and requires less time than the PSP hardware installation.

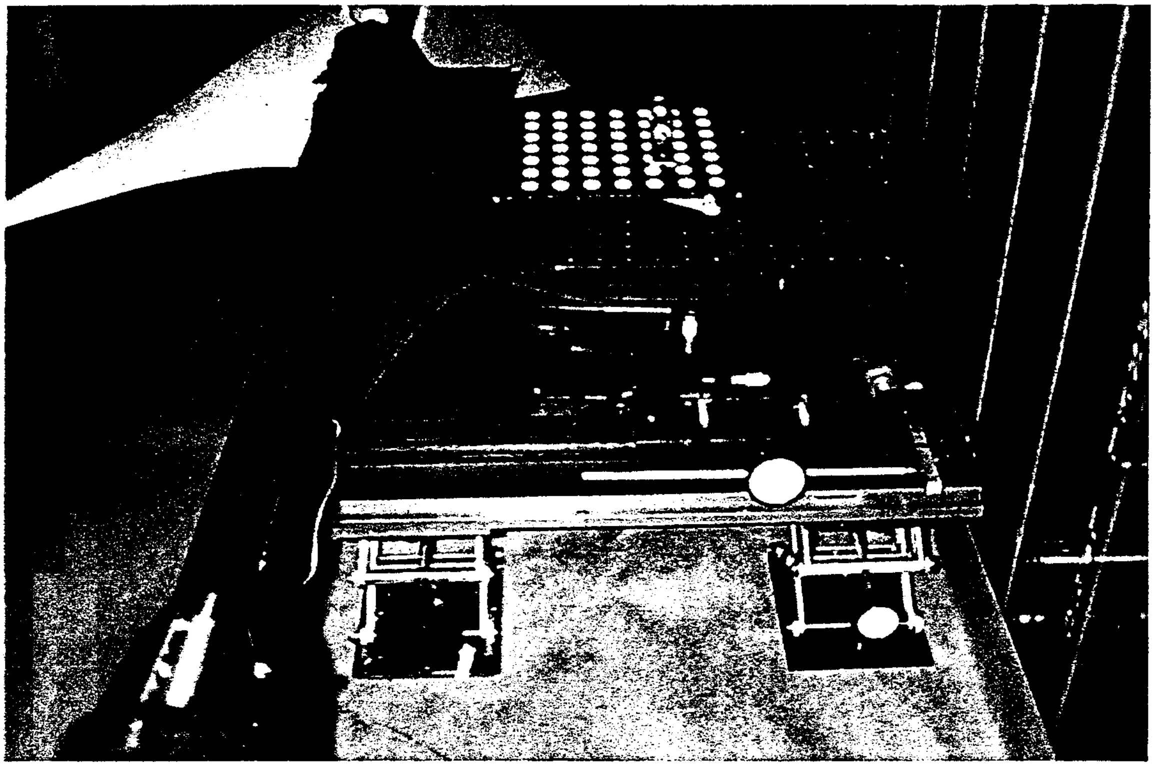
UPWT VMD System (concluded)

- The video signal is routed to a frame grabber controlled by a 120 MHz Pentium PC in the UPWT Data Room
- Detailed in-tunnel static calibrations are performed using a target plate to determine the camera position and pointing angles
- Wind-off pitch sweeps of the model (in the upright position) and retroreflective targets installed are then conducted
- Automated system analyzes several digitized video images at each angle of attack during the wind-off and wind-on pitch sweeps and displays "raw" values of the wing local angle of attack and vertical ("z") coordinates
- Commercially-available numeric computation and visualization software package is used to compute and plot final wing twist and wing bending results

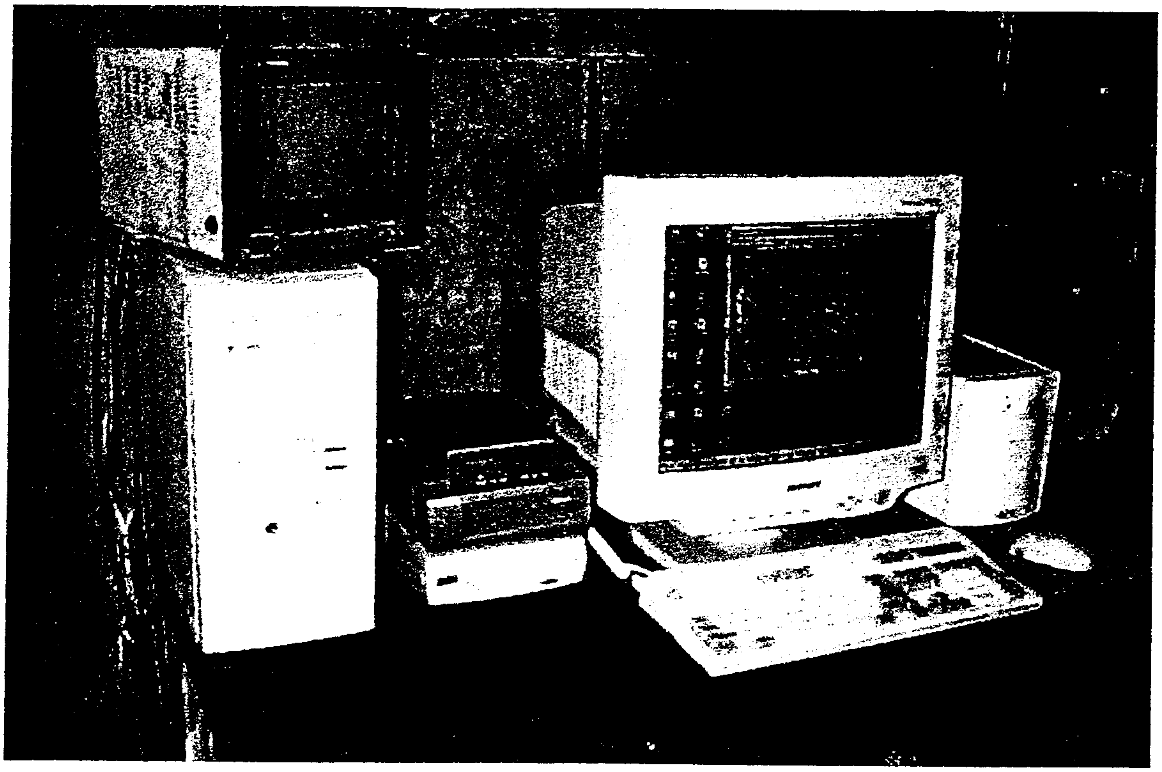
Images are acquired from the video CCD camera using a frame grabber board installed in a Windows 95-based PC. Acquisition of digitized video images is triggered by a "pickle switch" or a keyboard command, and the automated system identifies the model targets and analyzes several video images at each angle of attack. Tunnel test condition information is also acquired at this time from the wind tunnel data acquisition system via an RS-232 interface. The tunnel test conditions, test point information, and the values of the uncorrected local angle of attack and vertical displacement at all target rows are then displayed on-screen, at which point the system is ready for the next data point. Target plate calibrations and wind-off and wind-on data are acquired in the same manner. The calibration of the camera is a detailed procedure which uses a target plate rig constructed for the UPWT system and yields the camera location, pointing angles, and effective focal length. Wind-off pitch sweeps of the model in the upright position are conducted to verify the camera calibration and to provide static "tares" that are subtracted from the wind-on data. Post-run processing of the VMD data is done using a commercially-available software package that computes and plots the corrected wing twist and deflection results.



This is a close-up view of the 1.5%-scale HSR TCA 20 model with a VMD system calibration target plate placed on the right wing upper surface. The target plate consists of 49 targets with precisely known x- and y-coordinates measured on a NASA Quality Assurance validator. In practice, the target plate is mounted to a platform that has precise control of the y- and z-position of the plate relative to the model centerline. The target plate is a critical element in the determination of the VMD system camera position and pointing angles.



The calibration rig that is used to determine the camera constants (location, pointing angles, effective focal length) is shown in this photograph. The target plate is situated atop the rig and slides over the top of the wing surface. The x-position of the calibration assembly is set to provide a satisfactory image from the video CCD camera, and the y- and z-positions of the plate are varied using optical rail and lab jack arrangements. The y- and z-displacements of the target plate are measured using dial gauges (only one gauge is shown installed in the present photograph). As the calibration progresses, the calibration rig displacements measured with the dial gauges are compared to similar measurements obtained with the VMD system.



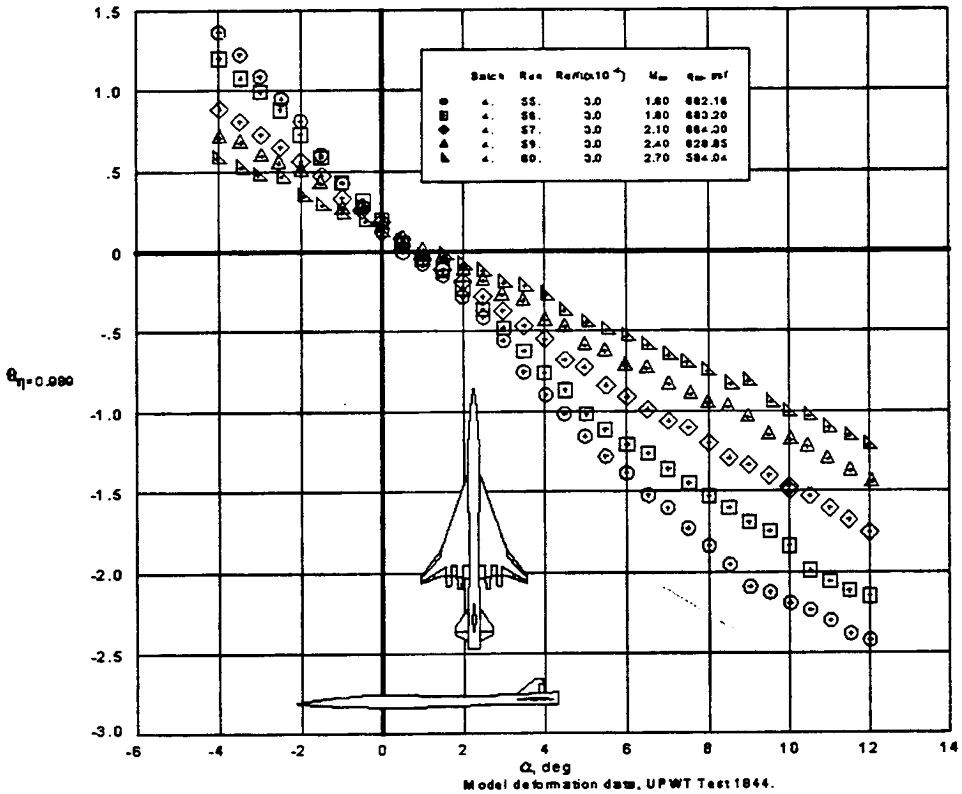
The host computer for the VMD system is illustrated in the above photograph. The mini-tower case contains the video frame grabber board that acquires, stores, and analyzes the digitized images. All image acquisition, processing, analysis, and plotting of the VMD results can be performed from this site.

VMD Applications to Date

- 1.675%-scale HSR Reference H model
- 1.675%-scale HSR TCA 2a model
- 1.675%-scale HSR TCA 20 model
- Test sections 1 and 2
- M=1.6 to 2.7, Re/ft=1-5 million
- α = -4° to 12°

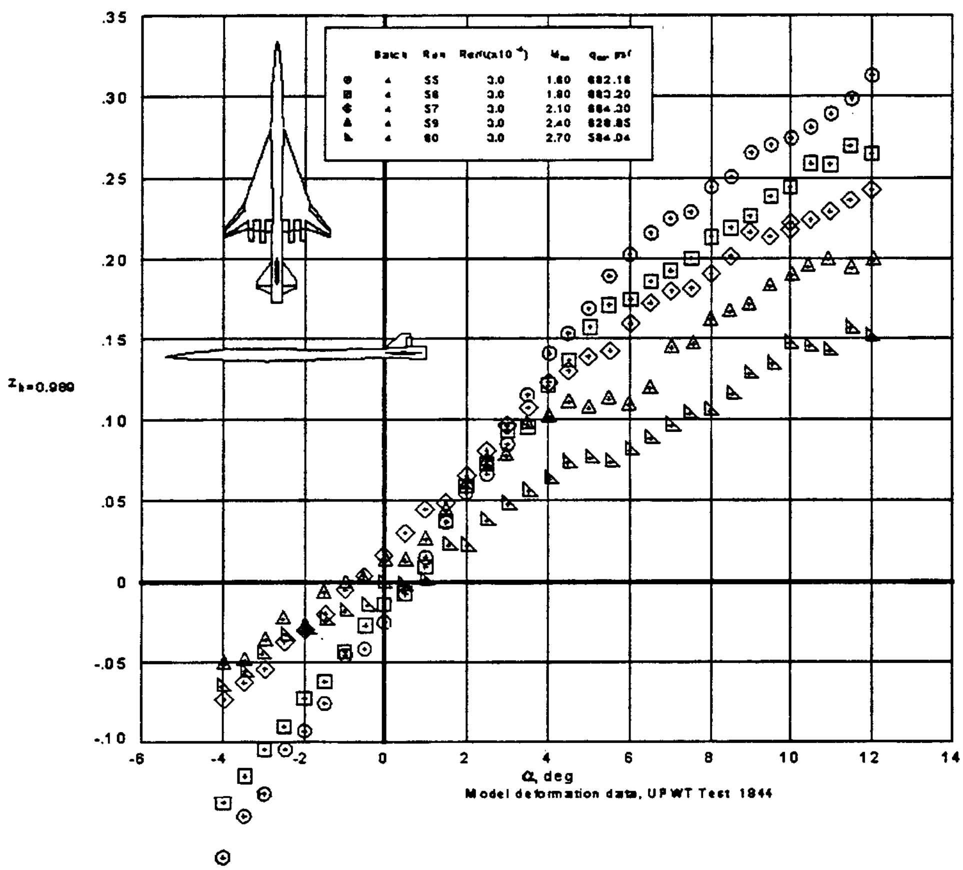
An early proof-of-concept test of the VMD system applied to a 1.675%-scale HSR Reference H model focused on the measurement of the wing twist at supersonic speeds. Each subsequent test led to enhancements of the UPWT VMD system. Primary improvements include additional target rows across the wing span to provide wing twist, deflection, and secondary model pitch angle measurements; improved method of "spatially mapping" the wind-off and wind-on results; and development of an effective target rig that significantly streamlined the camera calibration process. UPWT provides an excellent environment for this test technique, which has been successfully applied in both test sections over wide ranges of Mach number, Reynolds number, and angle of attack.

Mach Number Effect on Wing Twist
HSR TCA 20, Re/ft=3(10^6), UPWT Test 1844



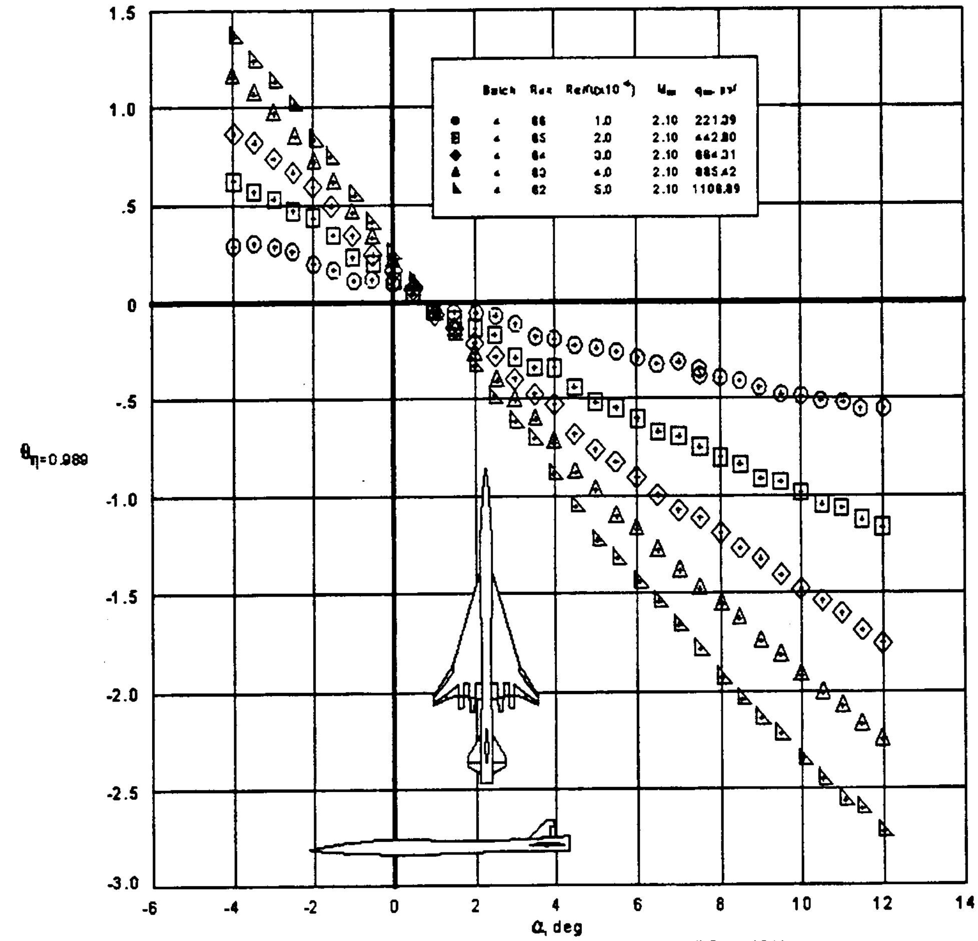
The effect of the free-stream Mach number on the wing twist at the y/(b/2)=0.989 span station is presented above. The Mach number varies from 1.60 to 2.70 at a constant Reynolds number per foot of 3(10^6). Increasing the Mach number decreases the wing twist (washout) at a given angle of attack. This effect is caused by the reduced wing lift as the Mach number is increased. A maximum twist angle of approximatly -2.9^0 was obtained at Mach=1.60 and $\alpha = 12^0$; at the same angle of attack, the twist angle was about -1.2^0 at Mach=2.70.

Mach Number Effect on Wing Deflection
HSR TCA 20, Re/ft=3(10^6), UPWT Test 1844



The Mach number effect on the wing deflection (bending) at the y/(b/2)=0.989 span station is shown in this figure. Increasing the Mach number decreases the deflection in the z (vertical) axis at a given angle of attack (less upward bending at the wing tip). The maximum deflection of approximately 0.31 inches was obtained at Mach=1.60 and $\alpha = 12^0$; the z displacement was 0.15 inches at Mach=2.7 and the same angle of attack.

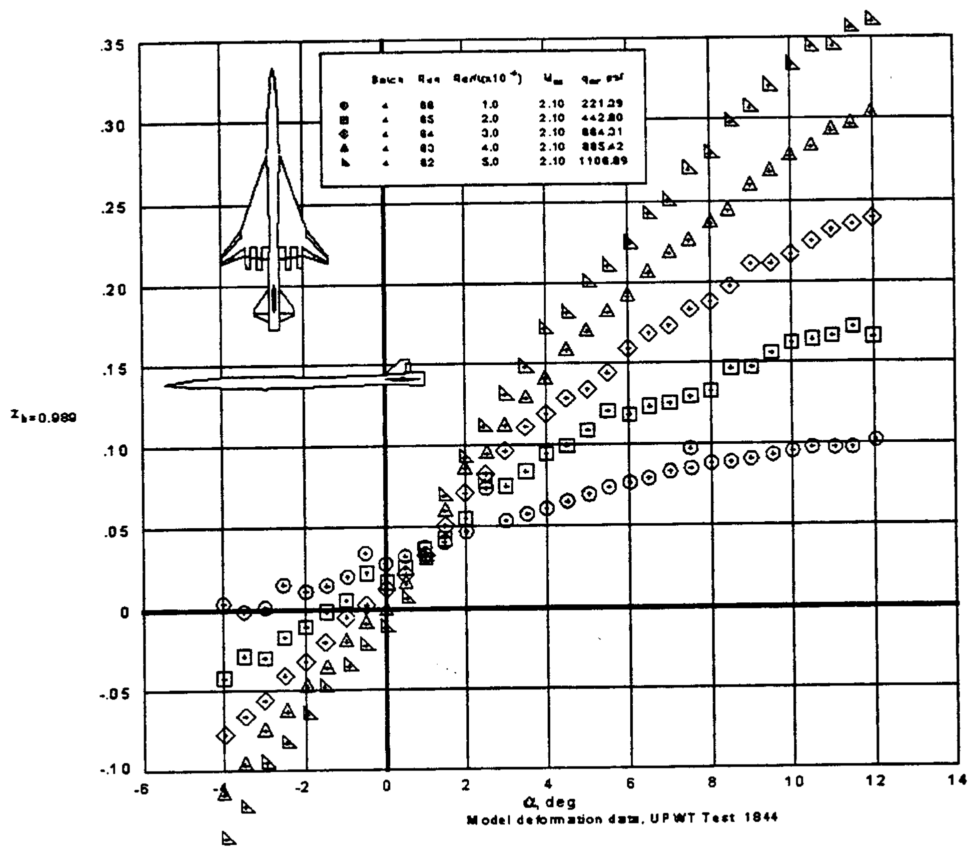
Reynolds Number Effect on Wing Twist
HSR TCA 20, Mach=2.10, UPWT Test 1844



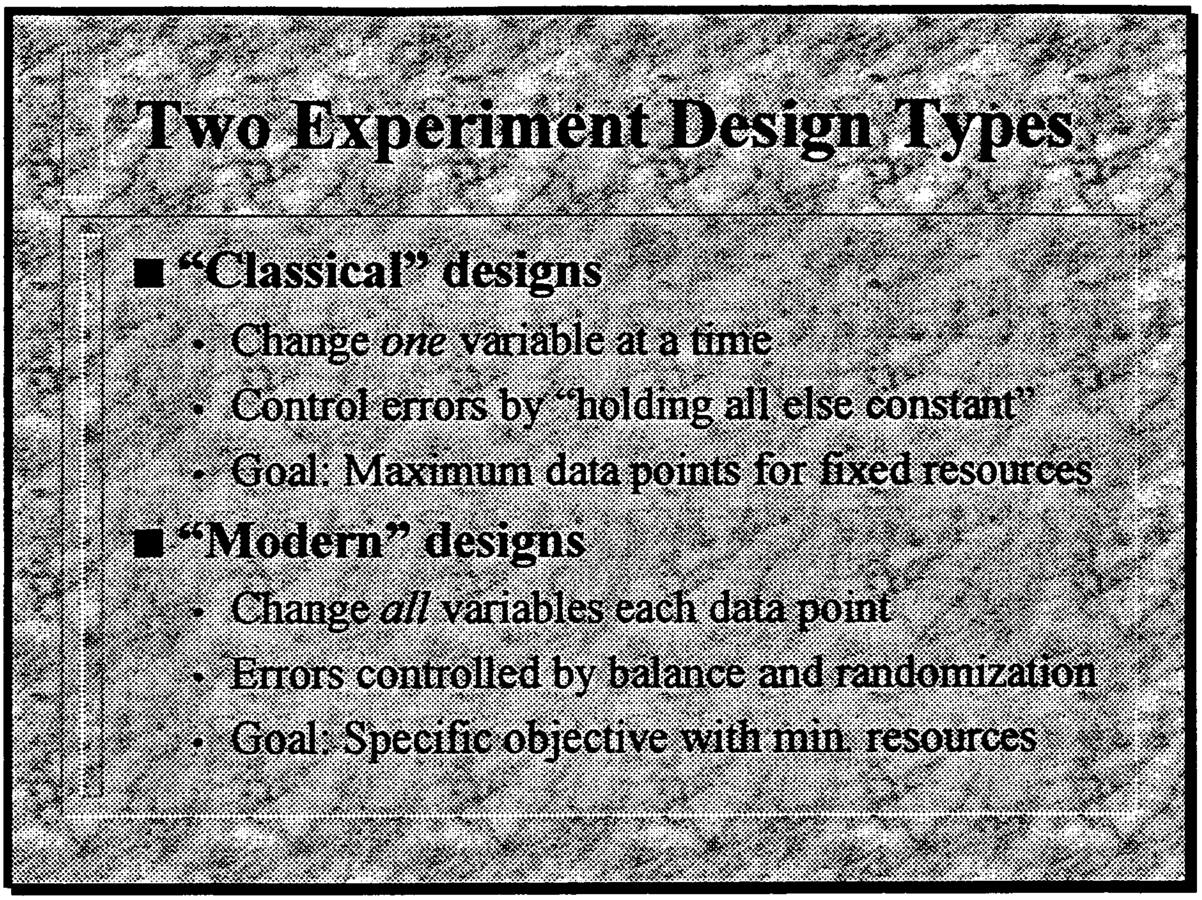
Model deformation data, UPWT Test 1844

The Reynolds number effect on wing twist at the y/(b/2) = 0.989 span station and a constant Mach number of 2.10 is shown in the data plot above. The Reynolds number per foot varies from 1.0 (10^6) to 5.0(10^6) in increments of 1(10^6). The trend in the data plot is more of a free-stream dynamic pressure ("q") effect than Reynolds number, since q varied from approximately 221 psf at Re/ft = 1(10^6) to 1100 psf at Re/ft = 5(10^6). The twist angle is approximately a linear function of the Reynolds number ("q"); for example, a five-fold increase in the Reynolds causes a corresponding increase in the twist angle near the wing tip. For the range of angle of attack tested, a maximum twist of -2.75^0 occurs at a Reynolds number of 5(10^6)/ft and α = 12^0, while the corresponding twist at Re/ft= 1(10^6) is -0.55^0.

Reynolds Number Effect on Wing Deflection HSR TCA 20, Mach=2.10, UPWT Test 1844

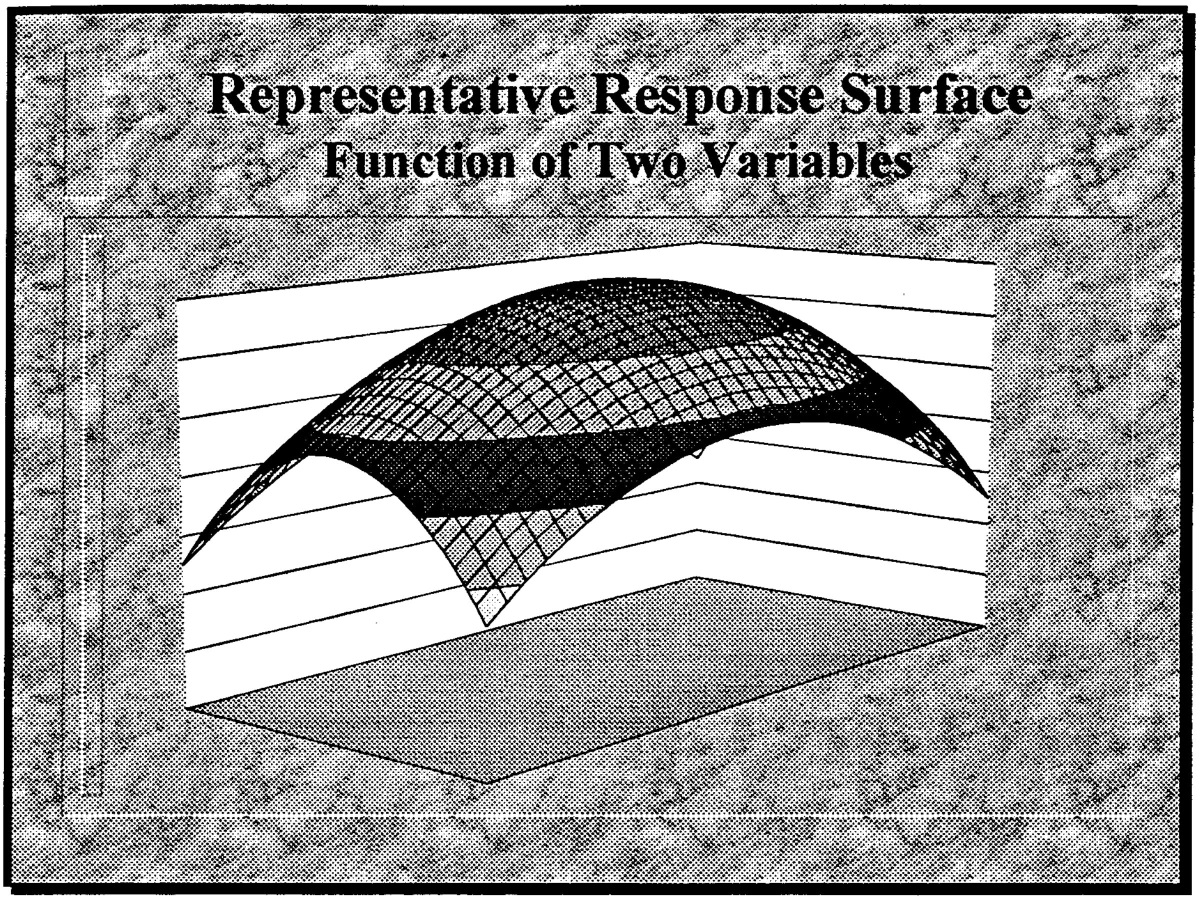


Wing deflection measurements obtained during a Reynolds number "sweep" at constant Mach number (Mach=2.10) are shown in this data plot. The Reynolds number per foot varies from 1.0 (10^6) to 5.0(10^6) in increments of 1(10^6). The z-displacement is approximately a linear function of the Reynolds number. Similar to the results shown in the previous figure, the primary factor affecting the wing displacement is the free-stream dynamic pressure. For the α -range in the present test, a maximum deflection of 0.36 inches occurs at a Reynolds number of 5 (10^6)/ft and $\alpha = 12^0$, while the corresponding displacement at Re/ft= 1(10^6) is 0.10 inches.



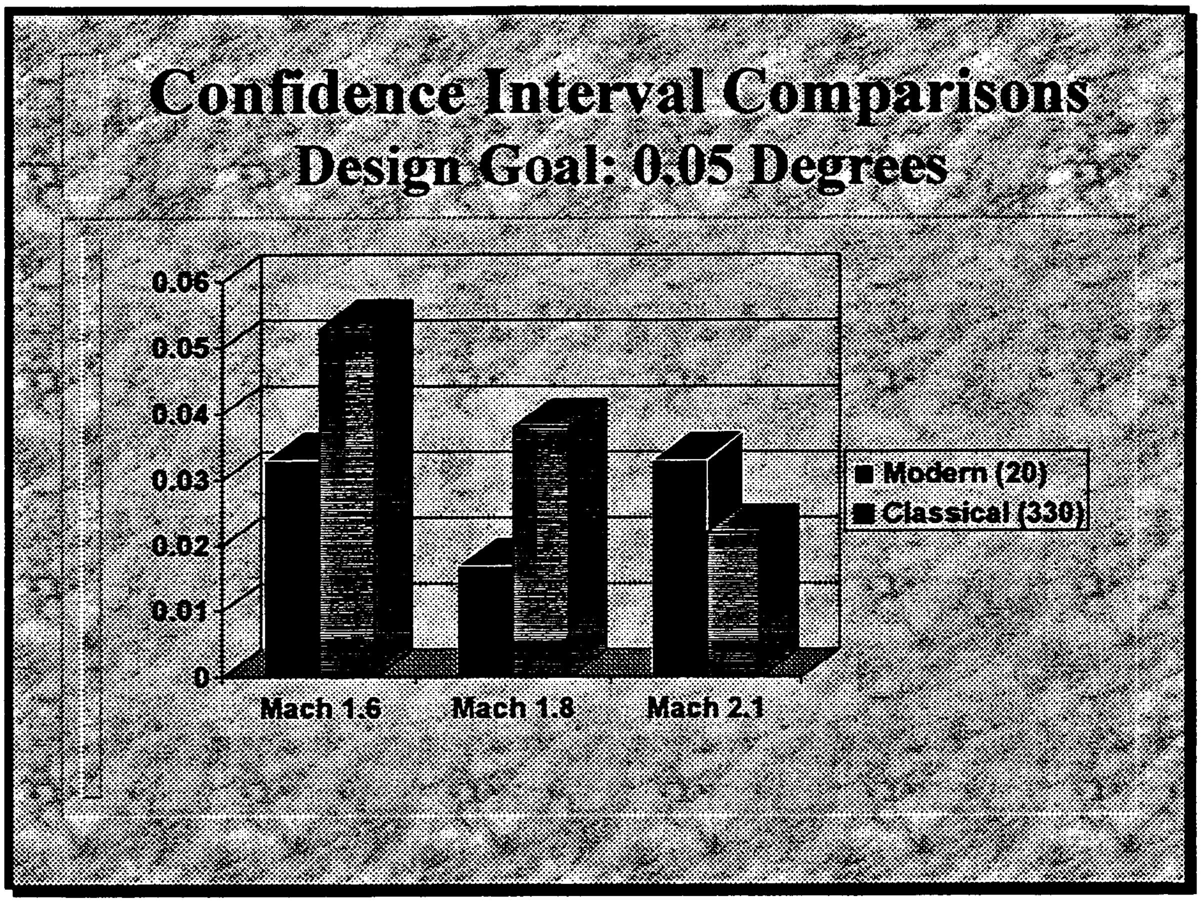
The term "Classical Design" is used to describe an approach to experimentation in which one variable is changed at a time while all other variables are held constant. Classical designs have been used in wind tunnel research at Langley since the earliest days of flight, and are widely used in wind tunnel testing elsewhere as well.

Today, important aircraft design decisions can turn on fractional drag count results, and practitioners of an alternative experiment design philosophy called "Modern Design" recognize the futility of "holding everything constant" which might affect results at this level. Instead, they exploit their knowledge of the stochastic nature of experimental variables to control error through balance and randomization. Modern and classical design philosophies also differ in their approach to productivity enhancement. Classical designers attempt to maximize the data volume for a given resource budget while modern designers attempt to achieve a specific technical result at a prescribed level of confidence with the smallest expenditure of resources possible.

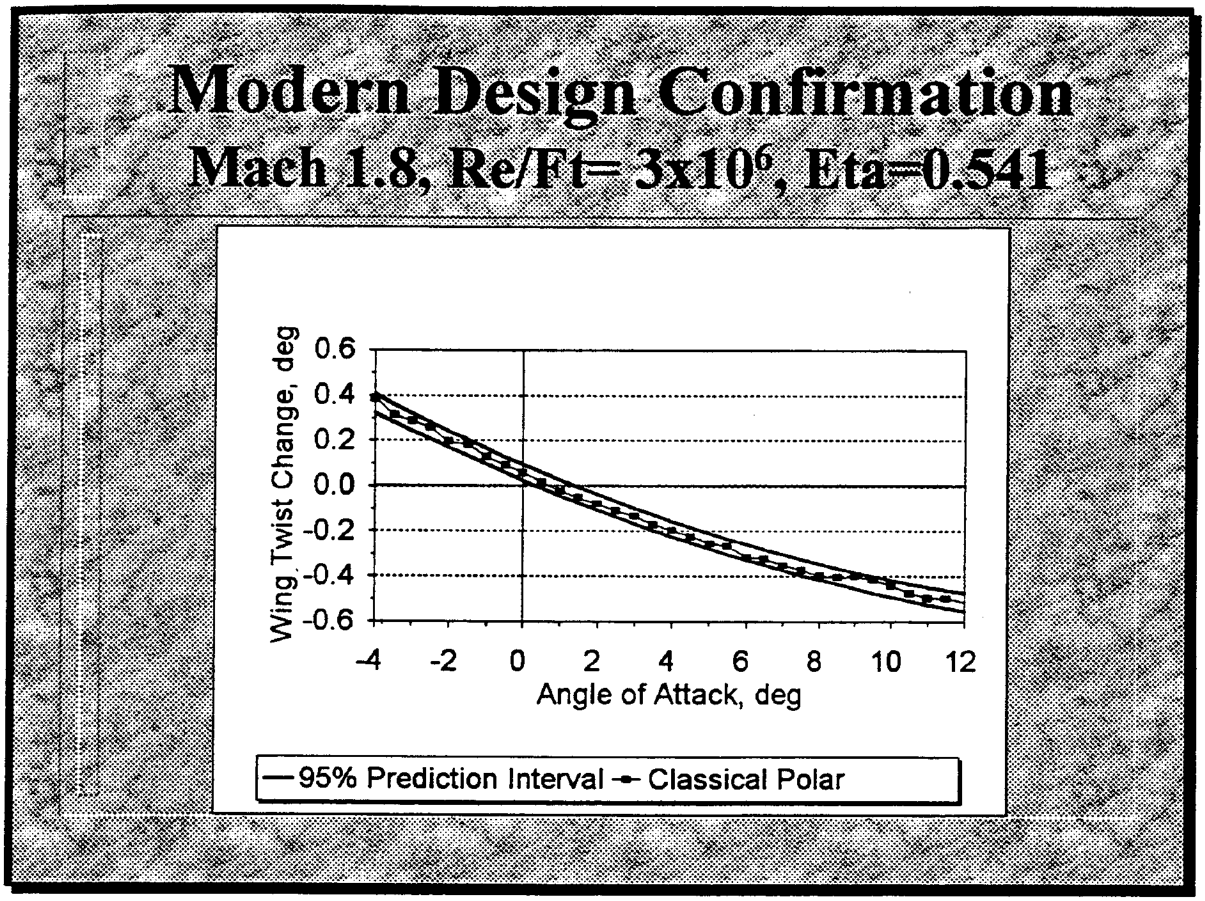


Classical designs divide a given inference space into a "grid" or "matrix" of test conditions at which response variables of interest are measured (forces, moments, etc.) The extent of this grid and the size of the cells which comprise it are influenced by the amount of resources available for a given test.

Modern design practitioners use the concept of a "response surface" to guide their design efforts. A response surface is a logical extension of the simple one-variable line graph in which the dependence of the response variable on all relevant independent variables is simultaneously considered in a small region of interest in the inference space. The extent of this region is purposely limited to that in which the response variable can be approximated adequately by a low-order Taylor series. Methods such as regression and contrast analysis are used to elucidate the response surface. Various curvature tests and optimization procedures are then used to quickly identify regions in the inference space which are the most interesting (peaks, ridge systems, etc.), which reduces resources that would otherwise be spent in less profitable regions.

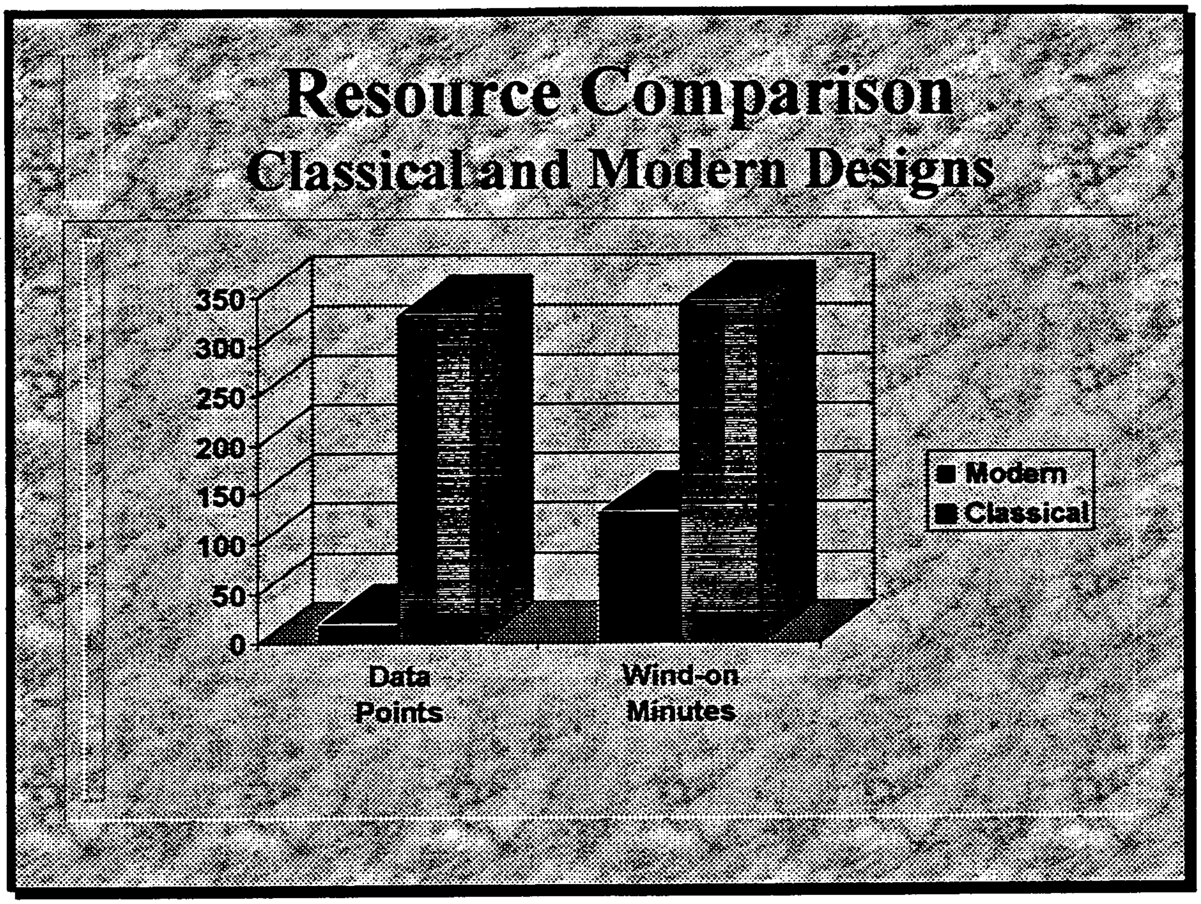


The aerodynamically-induced increase in wing twist for an HSR stability and control model has been measured for a range of angles of attack, Mach numbers, and Reynolds numbers as described elsewhere in this paper. A classical design requiring 330 data points was initially conducted, followed by a modern design to likewise quantify the wing twist change for the same model. The modern design required only 20 data points to define wing twist as a second-order response function in 3 variables with a design-goal precision of 0.05° at a prescribed 95% confidence level, given the 0.04° standard deviation in measured wing twist that was anticipated. The figure above compares 95% confidence intervals for the classical and modern designs. Both methods generated results with a precision that met the 0.05° design goal.



The two solid curves in the above figure mark the upper and lower limits of the 95% prediction interval for the modern design results at a given Mach number, Reynolds number, and normalized semi-span location. This modern design prediction was confirmed by plotting the 33 data points acquired on a different day at the same conditions, using the classical pitch-sweep method. Similar results were obtained at other combinations of Mach and Reynolds number.

Note that the above combination of Mach number and Reynolds number was never actually run in the modern design. This figure simply represents a slice through the modern design response surface in a direction parallel with the "angle of attack axis" at the specified values of Mach number and Reynolds number. This illustrates the fact that modern design response surface methods, once the response surface is adequately defined the response can be quantified for other combinations of the independent variables besides those measured directly.



The modern design method only requires enough data to fit a low-order (typically first or second order) function of the independent variables in regions of interest, plus sufficient additional data points to insure that design precision goals are met with a prescribed level of confidence. A Central Composite Rotatable Design (CCRD) was employed in this test which could accomplish these objectives with only 20 data points. This resulted in considerably fewer wind-on minutes than the classical design (approximately one third in this test.)

Additional comparison tests involving other response variables, other independent variables and different ranges of variables, and other facilities, must be conducted before a body of practical tunnel-testing experience will have been accumulated which is sufficient to warrant a general implementation recommendation. However, modern design methods have been shown in this test to have some promising potential for wind tunnel research in an era in which external pressures continue to dictate that more be accomplished with less.

Summary

- PSP and VMD systems are installed and operational at UPWT
- Test techniques provide global surface pressure mapping, qualitative surface flow visualization, and model deformation measurements (twist and bending) at supersonic speeds
- Expertise has been developed at UPWT that allows autonomous operation of both systems
- PSP and VMD systems are "works in progress" that will be subject to continued enhancements
- Modern experimental design technique was effective in capturing wing twist characteristics and may provide a means of streamlining the wind tunnel test process

Pressure-sensitive paint and video model deformation systems are installed in the NASA Langley Unitary Plan Wind Tunnel and have been operational since early 1996. The PSP and VMD systems has been effectively used in support of HSR supersonic wind tunnel testing to provide global surface pressure mapping, qualitative surface pressure field response to shock waves and vortex flows, and measurements of the wing local twist angle and deflections (bending). Time to set up and calibrate the PSP and VMD systems is one shift (each), while one shift for each technique is necessary to acquire a typical set of wind-on runs. Simultaneous installation of the PSP and VMD systems has been done, although the images from each system were acquired in a concurrent, rather than simultaneous, manner because of system conflicts. Future enhancements to these systems that may lead to a "turn-key" operation include the ability to remotely control all illumination sources, including mechanized shutters for the UV lamps to reduce the effects of photodegradation, and full automation of the image acquisition process. The experience gained from PSP and VMD testing in cooperation with ETTD has resulted in resident expertise at UPWT regarding virtually all aspects of the system operations (application of the PSP coating continues to be performed by ETTD). A Modern Experimental Design technique was used during a recent VMD test where all critical test parameters were varied at each of 20 data points. The resultant response surface proved effective in predicting the wing twist over ranges of Mach number, Reynolds number, and angle of attack.