HSR
High Speed Research - Configuration Aerodynamics
Langley Research Center

HSR Model Deformation Measurements from Subsonic to Supersonic Speeds

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HSR model deformation measurements from subsonic to supersonic speeds at several NASA facilities at Langley and Ames Research Centers are presented. The video model deformation (VMD) method has been used extensively for several years at NASA facilities for deformation measurements for both High Speed Research (HSR) and Advanced Subsonic Technology (AST) tests. Results for HSR models have been presented at two previous Configuration Aerodynamics workshops. Efforts are also underway to develop the projection moiré interferometry (PMI) method that offers potential advantages over the VMD method provided a number of operational difficulties can be overcome. At the current state of development, PMI is not ready for production wind tunnel testing, but after further development may serve to complement the VMD method (especially for measuring the deformation of control surfaces). A. W. Burner of the Experimental Testing Technology Division is the primary contact for the video photogrammetric method for measuring deformation. G. E. Erickson and W. L. Goodman are test engineers at the Langley Unitary Plan Wind Tunnel and 16-Foot Transonic Tunnel respectively of the Aero- and Gas-Dynamics Division. G. A. Fleming of the Fluid Mechanics and Acoustics Division is the primary contact for the projection moiré interferometry (PMI) method.

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This paper describes the video model deformation technique (VMD) used at five NASA facilities and the projection moiré interferometry (PMI) technique used at two NASA facilities. Comparisons between the two techniques for model deformation measurements are provided. Facilities at NASA - Ames and NASA - Langley where deformation measurements have been made are presented. Examples of HSR model deformation measurements from the Langley Unitary Wind Tunnel, Langley 16-foot Transonic Wind Tunnel, and the Ames 12-foot Pressure Tunnel are presented. A study to improve and develop new targeting schemes at the National Transonic Facility is also described. The consideration of milled targets for future HSR models is recommended when deformation measurements are expected to be required. Finally, future development work for VMD and PMI is addressed.

VMD APPROACH

• Single view photogrammetry
• Non intrusive (except targets)
• Automated processing
• Multiple images / data point
• Wind-off polars for calibration
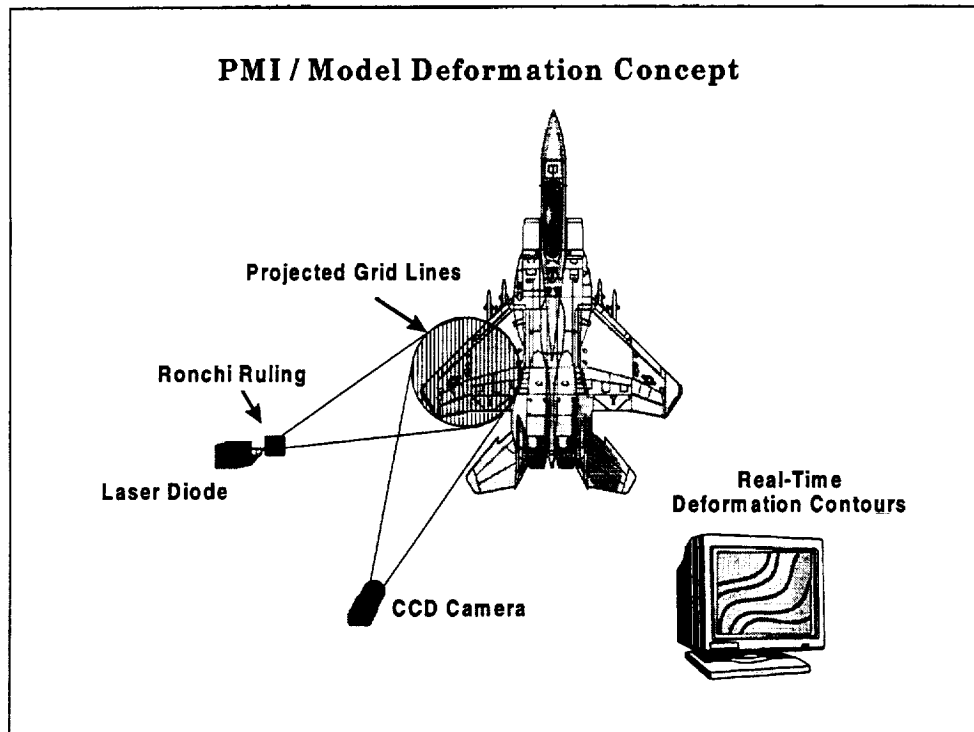• Angle change due to flow
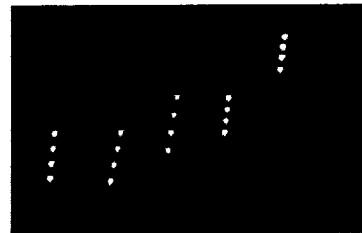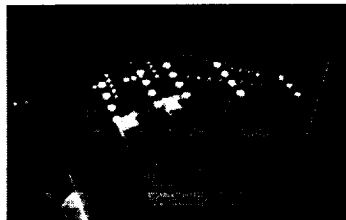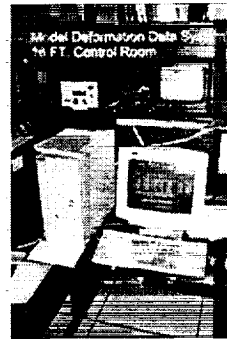
The video model deformation technique (VMD) consists of a single view, single camera photogrammetric solution of targets placed on the wing at known semispan locations. Except for these targets, which may have some minor effects on the aerodynamic data, the technique is non-intrusive. The basic hardware consists of a standard video-rate CCD video camera, light source usually located as close to the camera as possible (except for the National Transonic Facility), frame grabber board, and computer.   The computer used at the 16-Ft Transonic Tunnel is shown in the upper right photograph. Targets are typically placed on or near the fuselage to serve as control in addition to a number of semispan locations on the wing. Retroreflective targets applied to the right wing of a TCA model at the Unitary Wind Tunnel are shown in the lower left photograph. A high contrast image of retroreflective targets on the 4% Arrow Wing HSR model at the Ames 12-Ft Pressure Tunnel is shown in the bottom right photograph where the flow direction is upward on the image and the wing tip is to the right. Flat black paint was used to remove glints and increase target contrast. Image processing is used to automatically locate and compute corrected image plane coordinates for each of the targets. Single view photogrammetry is then used to determine the X (streamwise), Z (vertical) coordinates in object space, given the known Y (crossflow) coordinates. Slope angles and vertical displacements at specified chordwise locations are computed by linear least squares for each semispan station along the wing.

Projection Moiré Difference Contouring

Reference State — Deformed State ☰ Deformation Contours
(a)   (b)   (c)
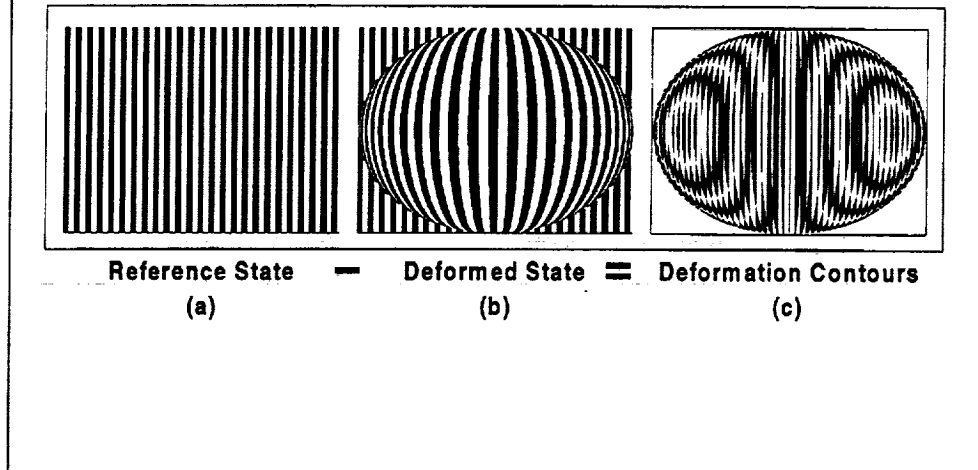
Projection Moiré Interferometry (PMI) is a second video-based model deformation technique under development at NASA - Langley. Based on grid line projection, PMI is an optically simple technique that can measure model deformation over the entire camera field-of-view. With reference to the chart above, assume a series of equispaced, parallel lines are projected onto a perfectly flat test article constituting a reference image (a). Under load, the test specimen will have deformed, and the projected grid lines will appear to lie in different spatial locations compared to the reference state (b). Subtracting images of the object in the reference and deformed conditions produces an image (c) containing moiré fringes (the low spatial frequency bands). Moiré fringes are observable in real time, providing the test engineer immediate video feedback regarding model attitude and deformation. Through off-line image processing and knowledge of the contour interval or *fringe sensitivity constant*, the topology of the deformed surface can be reconstructed.

PMI / Model Deformation Concept

Projected Grid Lines

Ronchi Ruling

Laser Diode

CCD Camera

Real-Time
Deformation Contours

The implementation of PMI as a wind tunnel model deformation instrument is shown schematically above. A pulsed, broad band 800-nm laser diode is used as the illumination source. Light from the diode passes through a Ronchi ruling, a binary grating of etched parallel lines, which causes grid lines to be projected onto the model surface. A conventional RS-170 video camera is used to image the region of interest within 1/10000 second exposure time to effectively *freeze* model position. Images of the model in both wind-off and wind-on conditions are acquired and processed off-line to obtain the deformation profile. Instrument sensitivity is determined by the projected grid line pitch and the angle between the projector and receiver. PMI systems constructed at Langley use laser diode illumination to permit (a) simultaneous operation with other optical instrumentation techniques, (b) lights-on facility operation, and (c) high peak power to investigate large objects. However, any incoherent light source, including white light, can be used. PMI typically requires no surface preparation. The only surface requirement is that some amount of diffusely scattered light be collected by the CCD camera. In some cases, highly polished models would require painting.

Preliminary PMI Data

LaRC UPWT, HSR NCV Configuration
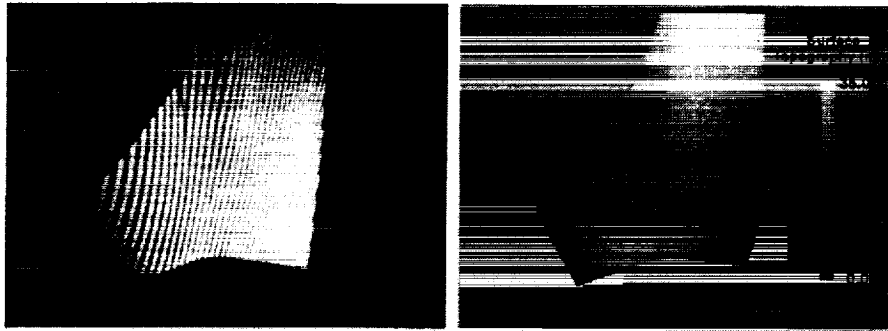
(a) PMI Projected grid lines, HSR NCV Wing   (b) PMI measured surface topology

The first Langley attempt at using PMI to measure model deformation of a fixed-wing aircraft occurred at the LaRC Unitary Plan Wind Tunnel in January, 1998. The model under investigation was a 1.675 %-scale HSR NCV configuration. Preliminary data and intermediate results are shown above for a single 1/10000 second exposure. Image (a) above is a raw PMI data image that has been dewarped to remove optical and perspective distortion. The projected grid lines are apparent. Further image processing of the image in (a) produces a surface topology as shown in image (b). Image (b) is an intermediate processing step, and is shown here only to demonstrate the type of information that can be obtained using PMI. To obtain wind-on model deformation data, the topology of the wing in its reference condition must be subtracted from image (b) above. Currently, image registration and scaling problems are causing difficulties at this stage of the data processing. Algorithms are currently under development to combat these problems and enhance data quality.

COMPARISON OF VMD AND PMI

VMD	PMI
• Operational	• Developmental
• 17 tests in 5 facilities	• 2 tests in 2 facilities
• Alpha sweeps only	• Alpha & beta possible
• Targets at each semispan	• No targets
• Data for discrete locations	• Nearly continuous data
• Rapid data acquisition	• Rapid data acquisition
• Near real-time angles	• Real-time def. Contours
• Rapid final data reduction	• May be days
• No laser	• Laser may be used
• 1 window	• 2 windows usually
• Model prep sometimes	• Model prep sometimes
• NASA LaRC, ARC	• NASA LaRC, DLR (ETW)

The VMD approach has been used to determine model deformation data for 17 tests in 5 NASA facilities over the last 2 years. The PMI approach under development has been used for 2 tests at 2 NASA facilities. While improvements and enhancements to both approaches are still underway, the VMD approach is more mature than the PMI approach for production wind tunnel testing. (The PMI system developed by DLR for the measurement of model deformation at the European Transonic Wind Tunnel (ETW) is also not currently ready for production testing.) Developments continue on PMI due to the limitations of VMD, not suffered by PMI, such as: (1) data is limited to alpha sweeps only, (2) targets must be applied, and (3) reduced data is only available at discrete locations where targets are located. Both approaches have rapid data acquisition, but at the current developmental stage of PMI, VMD has much faster data reduction with near real time reduction of angles and rapid (in minutes) reduction for twist and bending once wind-off polars are completed. Although a laser is not required for PMI, it does provide operational advantages when selective camera filtering is used. This includes immunity to test section lighting and the capability of simultaneous operation with other optical instrumentation systems. The PMI projector normally requires a window port in addition to the window port required for the PMI camera. It is sometimes necessary to apply flat black paint on regions of the model where glints obscure targets for the VMD approach or to provide a sufficiently diffuse surface for PMI.

**NASA FACILITIES
DEFORMATION MEASUREMENTS**

Langley
- **National Transonic Facility**
- **Transonic Dynamics Tunnel**
- **Unitary Plan Wind Tunnel**
- **16-Ft Transonic Tunnel**
- **14-by 22-Ft Subsonic Tunnel**
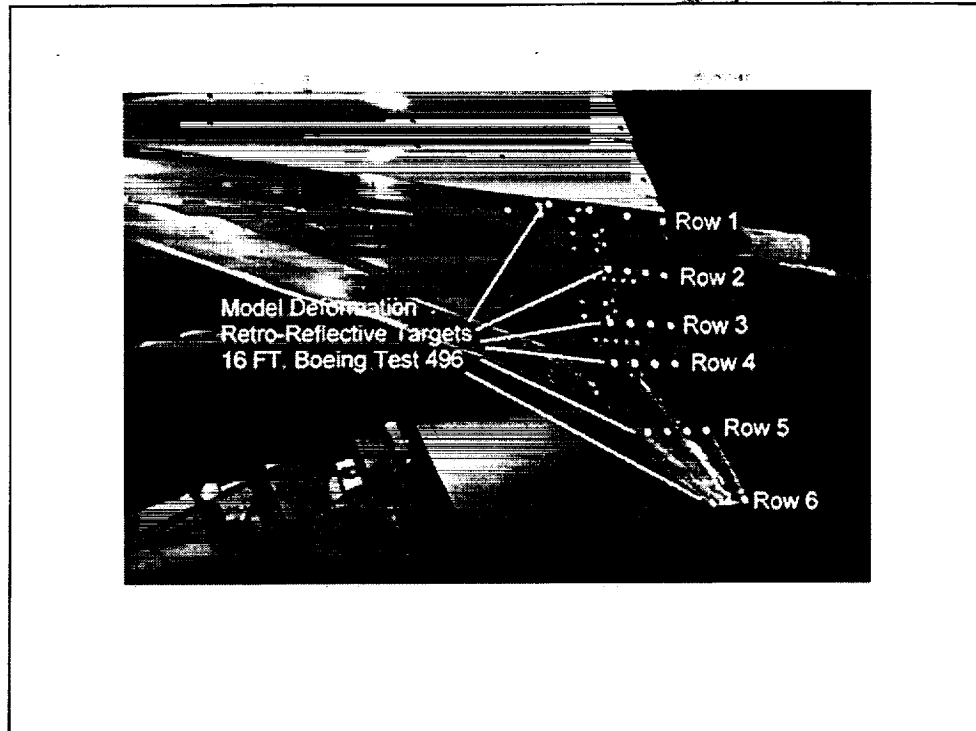
Ames
- **12-Ft Pressure Tunnel**

The PMI system has been used to measure rotorcraft blade dynamics at the 14-by 22-Foot Subsonic Tunnel and to measure deformation of an HSR model at the UPWT. Dedicated VMD systems are now operational in 5 tunnels at Ames and Langley. These facilities are the National Transonic Facility (NTF), Transonic Dynamics Tunnel (TDT), Unitary Plan Wind Tunnel (UPWT), and 16-Foot Transonic Tunnel (16-TT) at Langley and the 12-Ft Pressure Tunnel at Ames. Deformation measurements have been made on HSR models at all 5 of these facilities including sting mounted and post mounted full span models and sidewall and floor mounted semispan models. Each of these facilities presents unique challenges to the installation of measurement systems. The most difficult instrumentation challenges occur at the NTF where constraints imposed by operation in a high-pressure environment over a wide range of temperatures (+140 to -250 F) have had a significant impact on the continuing development, improvement, and optimization of instrumentation at the facility (particularly for the measurement of model deformation). For example, retroreflective tape targets have not yet been used at the NTF as in the other 4 facilities due to difficulties in locating a light source sufficiently close to the VMD camera in addition to concerns about the aerodynamic effects due to target thickness. Thus a special polished paint technique for targets has been developed and investigations continue on improved targeting schemes for the NTF.
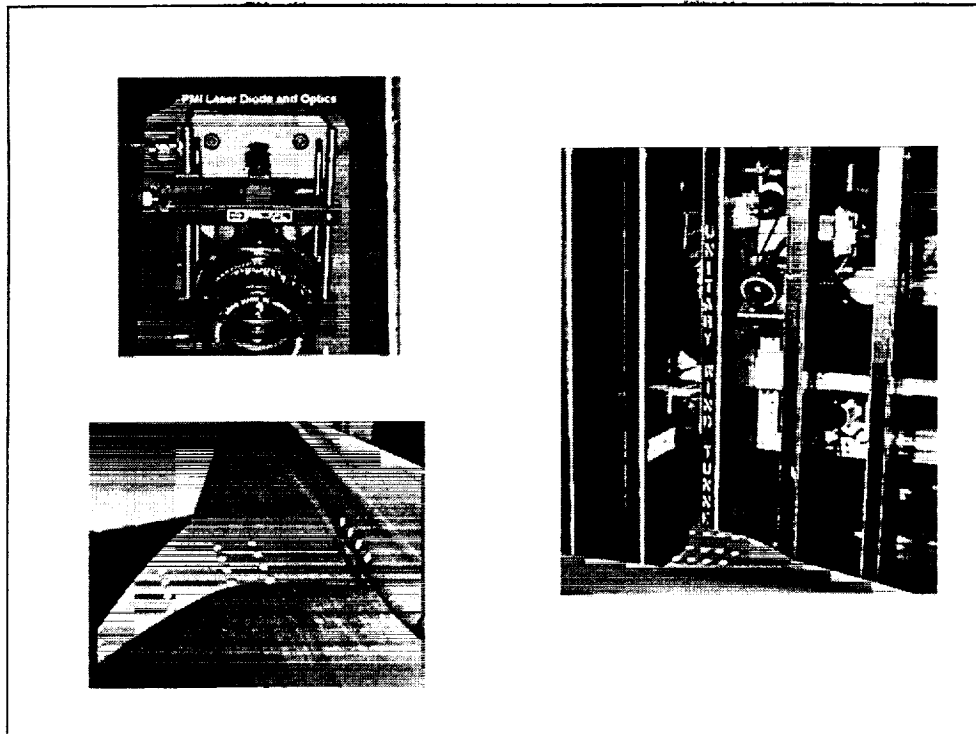
A recent test of the NCV model was conducted in test section #2 at the Langley Unitary Plan Wind Tunnel (test 1695). The primary purpose of the test was for advanced test technique development. Tests were conducted with the video model deformation (VMD) method, projection moiré interferometry (PMI) method, and Doppler global velocimetry (DGV) method. Data were taken for a number of runs throughout the test with simultaneous acquisition of VMD and PMI data. Toward the latter part of the test simultaneous VMD, PMI, and DGV data were acquired at 8 and 12 degree angle of attack. The upper left photograph shows the laser diode and optics of the PMI projector, mounted to the window webbing on the test section door opposite the PMI receiver and VMD camera. The photograph to the right shows the VMD camera with fiber optic ring light (lower) and PMI camera with filter (upper) mounted between the test section window webbing. The two cameras view the left wing of the NCV model which can be seen at the bottom of the right photograph. The mounting stand for the various DGV receivers can be seen in the right photograph behind the window webbing. Another view of the NCV model with retro reflective targets on the upper left wing and body is shown on the lower left. Targets were located on the body (η = -0.084) and at η = -0.415, -0.544, -0.762, and -0.992 along the wing span. The model was painted flat red to reduce potential specular reflections from the Doppler Global Velocimetry (DGV) system laser in order to improve the signal-to-noise ratio for the DGV measurements.
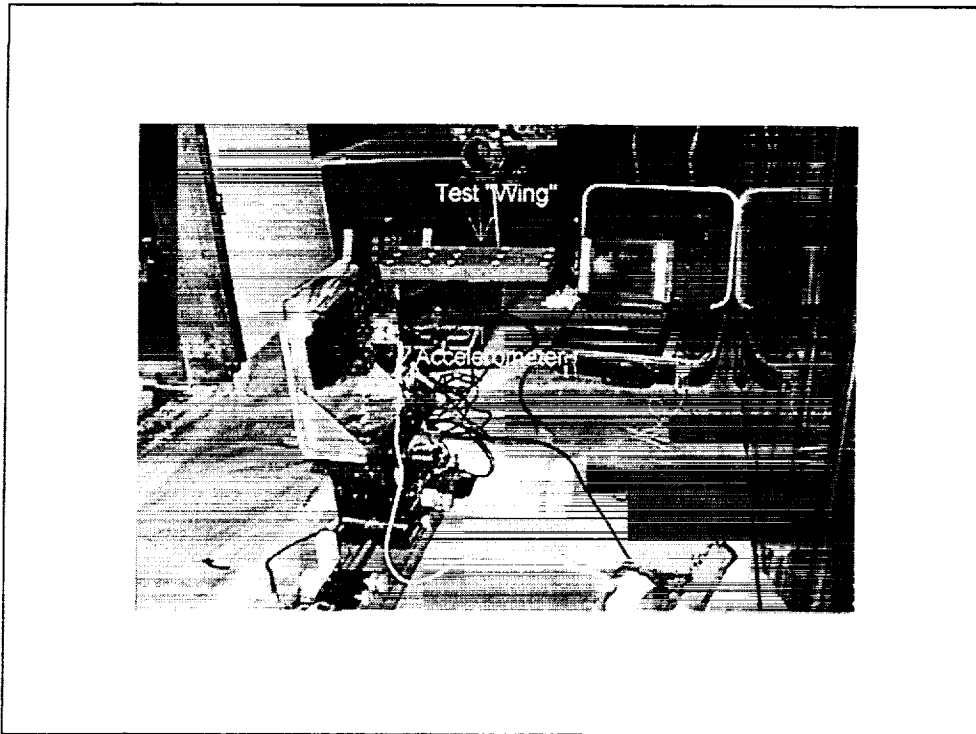
Prior to model installation, a test fixture was placed in the UPWT test section to conduct checkout and comparison tests of the VMD and PMI systems. A formal designed experiment developed by Richard DeLoach of the Experimental Testing Technology Division of NASA Langley was conducted to provide data to assess the relative and absolute performance of the two systems. The test fixture was aligned to be in the approximate location of the left wing of a model. Targets were applied at 5 semispan locations typical for HSR models at the UPWT. Precision accelerometers were used to measure the angle of attack and any accompanying roll of the test fixture which was mounted on a rotation stage and leveling mount. Two of the recently developed angle measurement systems (AMS) developed by the Experimental Testing Technology Division of NASA Langley were used to facilitate the angle measurements. Data were taken with both the VMD and PMI systems simultaneously over a set range of translations and pitch angles. A major concern for optical measurement systems at the UPWT is the large model translation in the flow direction as the pitch angle is changed. This large translation complicates the comparison of flow and no-flow data to determine wing twist and bending. The test fixture was mounted on vertical and horizontal translation stages in order to translate both in the flow direction and vertically to simulate typical motion of a model during testing at the facility. The amount of vertical and horizontal translation was set with gauge blocks.

The photograph above shows retroreflective targets placed on the lower right wing of a TCA model at the Langley 16-Foot Transonic Tunnel. The lower surface of the left wing has pressure paint applied with black reference targets. At the Ames 12-Ft, Langley 16-Ft and Langley UPWT a new version of the VMD system, developed by the High Technology Corporation, has been used to track PSP reference targets (using UV light sources) at the same time as PSP data is being taken. The simultaneous acquisition of pressure paint and deformation data would reduce the amount of time required for testing, thus increasing wind tunnel productivity. Currently the low level of fluorescent light from the pressure paint causes poor contrast images on the VMD system, resulting in marginal target tracking robustness. Camera integration times longer than the standard 1/60 second may be necessary to improve the image contrast and hence the reliability of the target tracking. Developments to further unify various advanced optical test techniques is crucial to increased productivity, especially as the number of "competing" optical techniques for various wind tunnel measurements continues to increase.
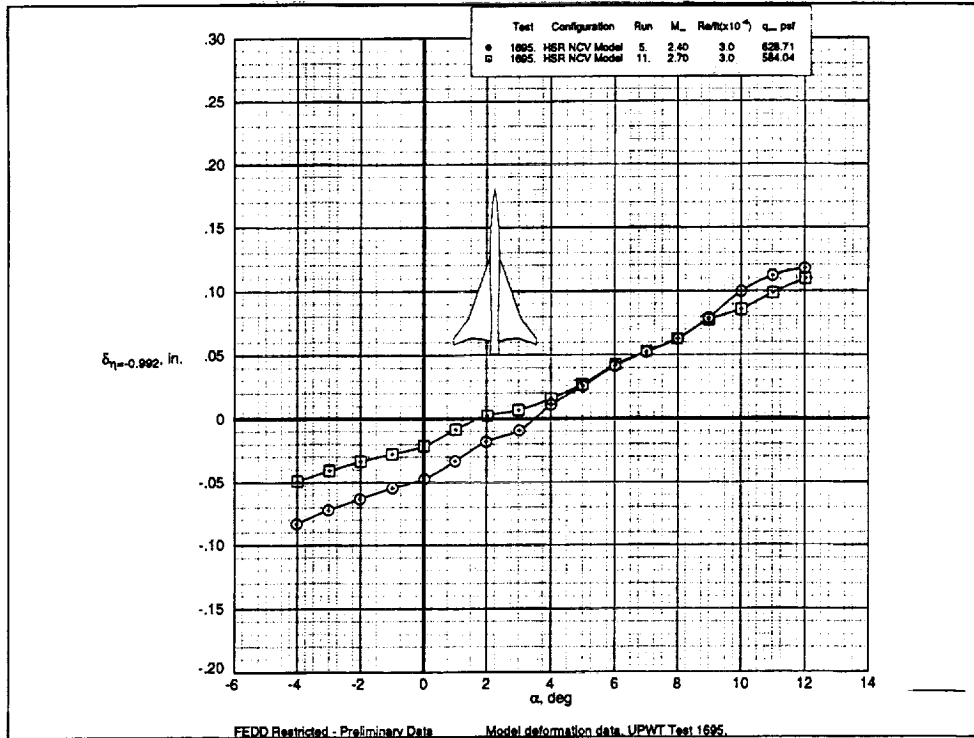
Model deformation data, UPWT Test 1695.   Mach = 2.4
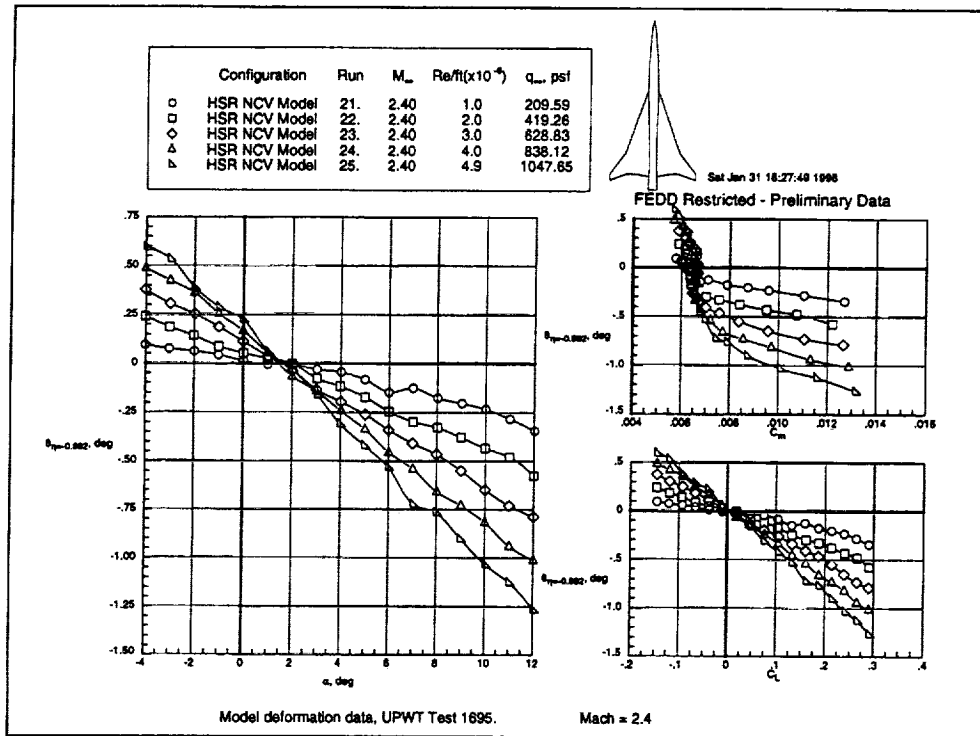
An HSR NCV model was recently tested (test 1695) at the Langley Unitary Plan Wind Tunnel test section #2. Data for the aerodynamically induced wing twist near the wing tip (-0.992 semispan) for Reynolds number sweeps at constant Mach number = 2.4 are plotted above versus alpha, C_L, and C_m. Reynolds number variations are obtained by changing the dynamic pressure, thus the plots above reflect the dynamic pressure effect on aeroelastic wing twist. The maximum wing twist of -1.25 deg at Mach 2.4 occurs at a Reynolds number of 4.9 million. The nearly linear change in twist as a function of alpha has been observed on a number of HSR models.
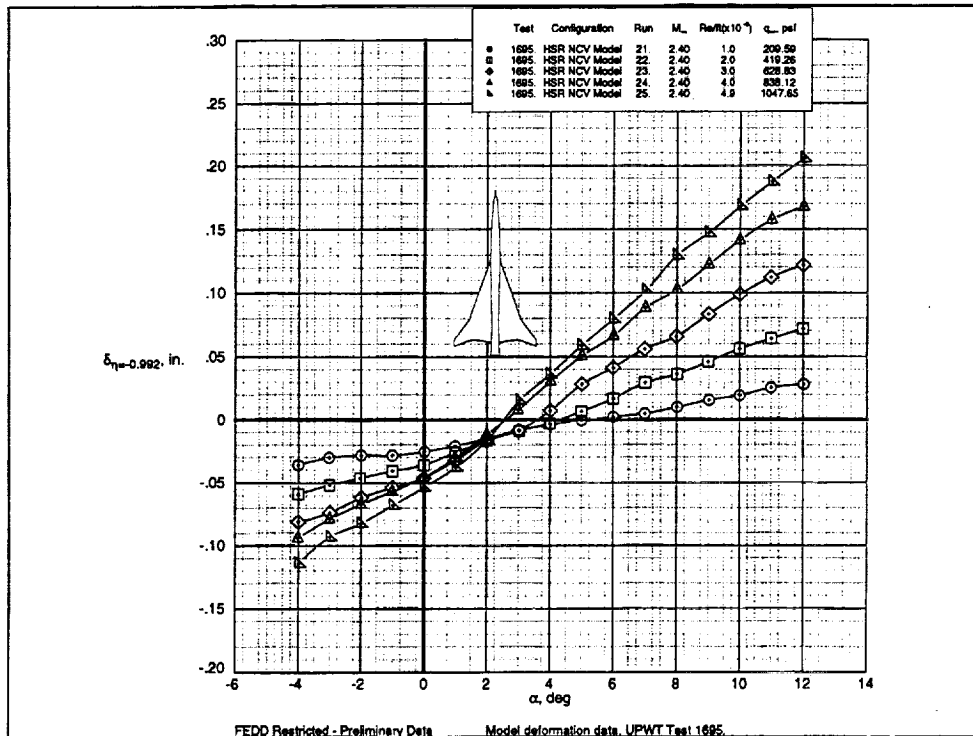
The vertical displacement near the tip corresponding to the previous plots is shown. For each Reynolds number case, the displacements are nearly equal at alpha ~ 2 degrees with a magnitude of -0.017 inches. Note, however, that zero induced twist and equal twist coincide at approximately 1.5 degrees on the previous plot of wing twist versus angle-of-attack. One might expect that the displacement would be zero when the twist is zero. Whether this discrepancy is an indication of error has not been determined.

Model deformation data, UPWT Test 1695.   Re/ft = 3.0 x 10⁶
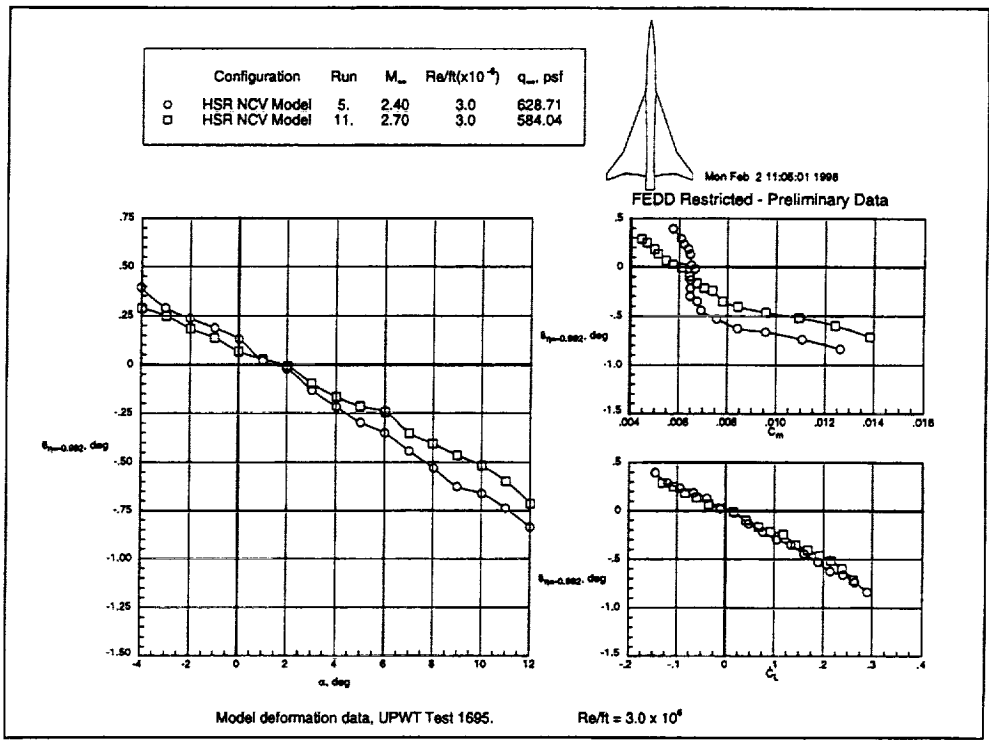
A comparison of the induced wing twist near the wing tip for Mach 2.4 and Mach 2.7 is plotted above for test 1695 at the Langley UPWT. The data also contains a small dynamic pressure effect which tends to increase induced twist for the Mach 2.4 case. However, this does not totally account for the increased twist with decreasing Mach number that has been observed for several different HSR models. Note the C_L plot de-emphasizes the induced twist differences while the differences are accentuated in the C_m plot.

Test	Configuration	Run	M∞	Re/ft(x10⁻⁶)	q∞ psf
● 1695.	HSR NCV Model	5.	2.40	3.0	628.71
□ 1695.	HSR NCV Model	11.	2.70	3.0	584.04

$\delta_{\eta=-0.992}$, in.

α, deg

FEDD Restricted - Preliminary Data   Model deformation data, UPWT Test 1695.

The vertical displacements near the tip corresponding to the twist plots
from the previous page are shown above. Note that the zero
displacement for the Mach 2.4 plot occurs at 3.5 deg alpha whereas the
zero induced twist occurs at 1.5 deg alpha. The zero displacement and
twist coincide for the Mach 2.7 data at 2 deg alpha. Comparisons of
displacement and twist data may assist in uncovering potential
discrepancies in the deformation data.

1583

TCA MODEL #5
LaRC 16-FT TEST 496
**BASELINE CONFIGURATION**
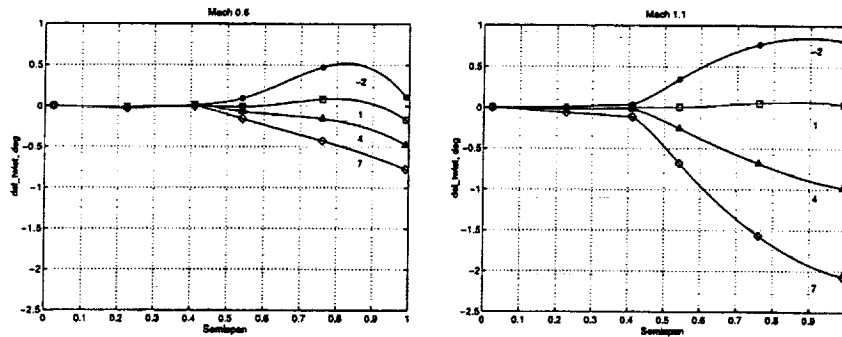
The data above shows load induced wing twist versus normalized semispan for the HSR TCA model #5 tested at Mach 0.6 and Mach 1.1. Testing was performed in the Langley 16-Foot Transonic Tunnel (Test 496). Data for the baseline configuration without deflected flaps is shown for alpha = -2, 1, 4, and 7 degrees. Data were also taken at 0.9 Mach number. Data taken at the test section wall flat settings for the various Mach numbers indicate that the flat setting has little effect on the measured twist, but causes a zero shift in displacement of up to 0.07 inches that varies with semispan station. For the data presented here separate wind-off calibration runs were taken at the appropriate flat setting for each mach number. A comparison of the baseline configuration and configurations with leading and trailing edges deflected at Mach 0.6 and 1.1 for the test 496 are shown on the following plots. Again, the alphas shown are -2, 1, 4, and 7 degrees. Note that the smaller chord at the tip (semispan near 1) results in less resolution for angle measurements since the targets at the tip span less distance on the image plane.
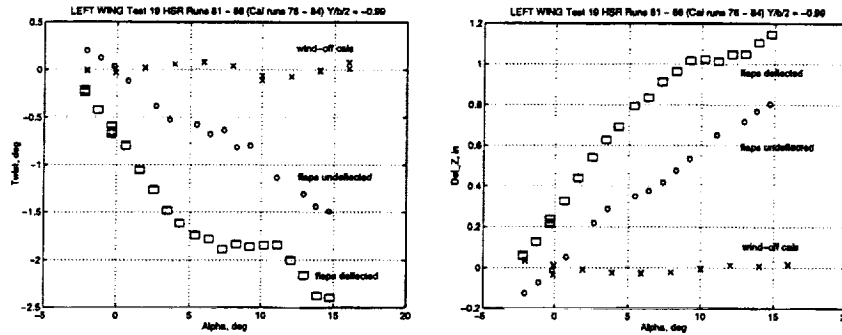
TCA MODEL #5
LaRC 16-FT TEST 496
MACH 0.6
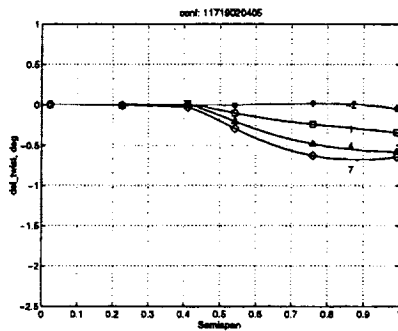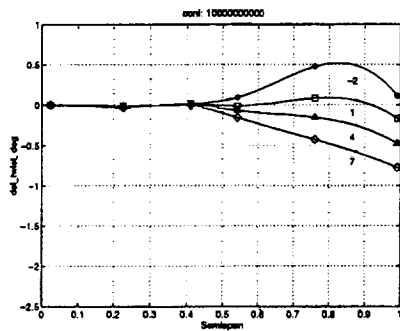
TCA MODEL #5
LaRC 16-FT TEST 496
MACH 1.1
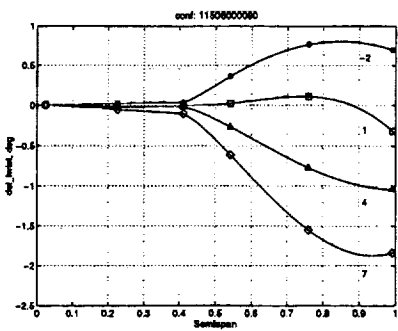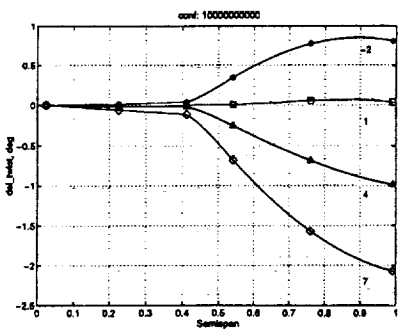
**4% ARROW WING LOW SPEED HIGH LIFT MODEL
AMES 12-FT PRESSURE TUNNEL
MACH = 0.225, Re = 8.51 X 10^6, Q = 435 PSF**

Aerodynamically induced wing twist near the wing tip (0.99 semispan) versus alpha for the 4% Arrow Wing HSR model at the Ames 12-Ft Pressure Tunnel is presented above. The change in vertical displacement, Z, versus alpha relative to wind-off is also presented. The Mach number was 0.225, the Reynolds number per foot was 8.51 million, and the dynamic pressure was 435 psf. Data for flaps deflected (squares) and undeflected (circles) are presented. Residuals from wind-off calibration runs (X) are also shown. Wind-off calibration runs use tunnel data for alpha which is not corrupted by sting bending calculations or dynamics associated with wind-on conditions that can lead to bias errors for inertial sensors mounted in the model. Polynomial fits are made to the calibration data to be applied to the wind-on data. The wind-off calibration runs provide an in situ angle calibration near the time that VMD data is taken. Wind-off calibration runs serve to remove the vertical translation that normally occurs due to the model being pitched. Wind-off calibration runs which bracket the wind-on runs also serve as a system stability check. Wind-off calibration runs are especially critical for facilities such as the National Transonic Facility where large temperature and pressure excursions may occur.
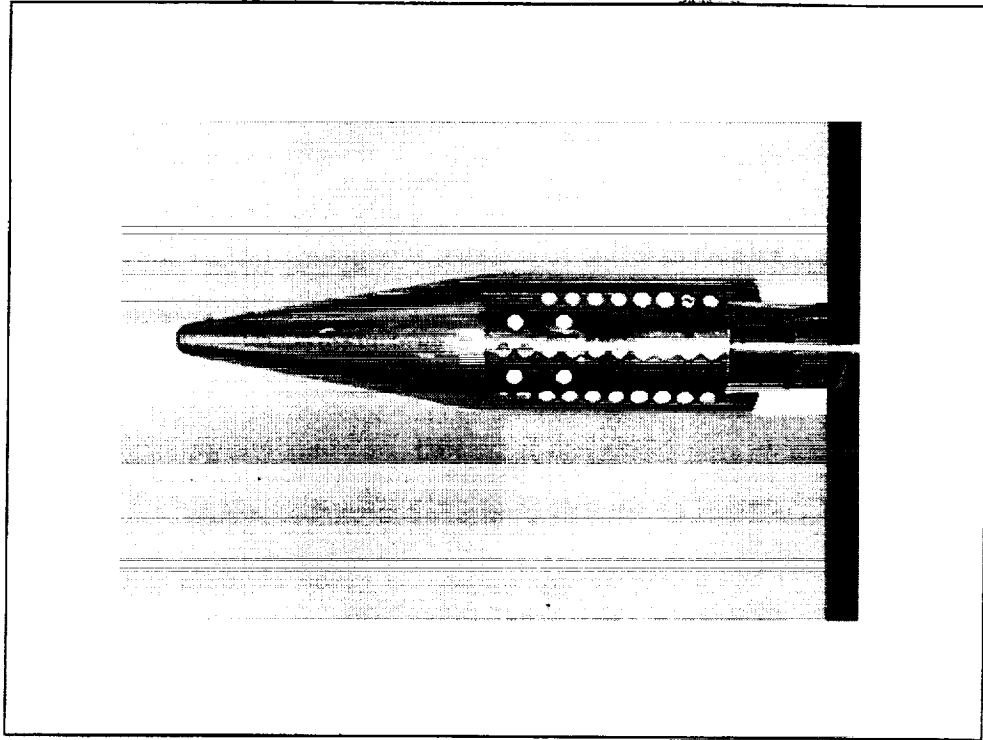
An experiment is ongoing at the National Transonic Facility to improve existing methods and develop new methods for applying targets that lessen their potentially negative effect on aerodynamic data. The calibration cone above has been tested at the facility (and will be tested again in April) with a variety of targets including polished paint applied directly to the surface. In addition milled targets have been tested with filler over white paint, retroreflective tape, fluorescent dye and filler mixture, and retroreflective paint. An advantage of milled targets, besides removing the step height, is that permanent targets are available that can be accurately determined with a 3-D coordinate measurement machine prior to testing. Subsequent tests with the model will then already have targets installed at known locations and at the same locations as previous tests. The time to install targets will be essentially eliminated during a test. If retroreflective tape is placed in milled locations, the step height of 0.004 inch is removed, but the surface roughness can be as large as 200 μinches. There are retroreflective tapes with surface roughness down to 20 μinches, but light return from these tapes is reduced. For polished paint targets applied directly to the wing surface there is no abrupt step (only a gradual rise to 0.0005 inch with surface roughness of 5 μinches) compared to the tape targets without milling. Consideration should be given to retroreflective tape (or polished paint) milled targets for future HSR models where deformation measurements are required.

FUTURE WORK

VMD

- **Tests at 5 NASA facilities**
- **Uncertainty analysis**
- **Robustness and speed**
- **Reduce and quantify target effects**
- **Simultaneous measurements with PSP**

PMI

- **Tests on actively controlled aircraft elements**
- **Uncertainty analysis and system characterization**
- **Image processing to increase speed and data quality**
- **Fully 3-D deformation (long term)**

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