Model Deformation Measurement Technique - NASA Langley HSR Experiences

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Model deformation measurement techniques have been investigated and developed at NASA's Langley Research Center. The current technique is based upon a single video camera photogrammetric determination of two dimensional coordinates of wing targets with a fixed (and known) third dimensional coordinate, namely the spanwise location. Variations of this technique have been used to measure wing twist and bending at a few selected spanwise locations near the wing tip on HSR models at the National Transonic Facility, the Transonic Dynamics Tunnel, and the Unitary Plan Wind Tunnel. Automated measurements have been made at both the Transonic Dynamics Tunnel and at Unitary Plan Wind Tunnel during the past year. Automated measurements were made for the first time at the NTF during the recently completed HSR Reference H Test 78 in early 1996. A major problem in automation for the NTF has been the need for high contrast targets which do not exceed the stringent surface finish requirements. The advantages and limitations (including targeting) of the technique as well as the rationale for selection of this particular technique are discussed. Wing twist examples from the HSR Reference H model are presented to illustrate the run-to-run and test-to-test repeatability of the technique in air mode at the NTF. Examples of wing twist in cryogenic nitrogen mode at the NTF are also presented.

Facilities

- National Transonic Facility
- Transonic Dynamics Tunnel
- Unitary Plan Wind Tunnel
- 16-Foot Transonic Tunnel

Model Deformation measurements for HSR models have recently been made at three NASA Langley Research Center facilities: the National Transonic Facility (NTF), the Transonic Dynamics Tunnel (TDT), and the Unitary Plan Wind Tunnel (UPWT). Dedicated video measurement systems to determine wing twist and bending are available at the NTF and the TDT. Successful results during HSR test 1651 last year at UPWT with a temporary system led to the decision to procure a dedicated system for that facility as well. In addition, a feasibility study has been initiated to determine the practicality of a similar measurement system at the 16-Foot Transonic Tunnel. The NTF has had a limited capability for model deformation measurements since 1984. Instrumentation development at the NTF led to the current technique. The first automated measurements of wing twist and bending were made at the TDT in 1994 where the application of high contrast targets on the wing made possible the use of image processing techniques to automatically determine the image coordinates of the targets. Data has been taken at the TDT for several tests of a rigid semispan HSR model. The first automated measurements of wing twist made at the NTF occurred in early 1996 during HSR Reference H Test 78. A polished paint technique was use to create high contrast white dot targets on a flat black background which enabled the automated measurements at the NTF.

NTF Instrumentation Concerns

- **120° F $\Rightarrow$ -250° F**
- **9 atm**
- **Limited access and mounting options**
- **Productivity**
- **Expense**
- **Conflicting requirements of optical techniques**

The constraints imposed by operation in a high pressure environment over such a wide range of temperatures have had a significant impact on instrumentation development for the NTF. Even though the facility has been operational since August 1984, instrumentation development, improvement, and optimization continues. All of the currently available optical measurement techniques as well as those under consideration must be able to accommodate the limited access and mounting options at the NTF. The increased importance of productivity and the very high cost of tunnel operation make it very difficult to justify dedicated run time for test technique development or enhancement. Another instrumentation development problem which has recently become more apparent is the competition between various optical techniques for lighting, viewports, and mode of operation. During the recent HSR Test 78, fluorescent mini-tuft and wing twist data were taken together for some runs. This required manual changing of the test section lighting for each point and an additional delay to be introduced into the wing twist measurement system in order to accommodate both measurement systems. As temperature and pressure sensitive paints and other flow visualization techniques are employed at the NTF, the competition between the various techniques will worsen.

Question

Should some small fraction of polars be set aside for test technique development, enhancement, and uncertainty analysis at the NTF?

The setting aside of some small fraction of polars for test technique development, enhancement, and uncertainty analysis should be viewed as an investment in the future. Such an investment will pay off in the long term with increased measurement capability, productivity, and lower cost per useful information.

Model Deformation

- **Wing Twist**
  more important
  AOA

- **Wing deflection or bending**
  less important
  harder to verify

In discussions about model deformation measurement requirements among a number of people involved in aerodynamic testing, the determination of the induced wing twist under aerodynamic load appears to be the primary concern, with wing deflection (bending) being of secondary importance. In addition, angle measurements (not deflection) occur naturally at wind tunnels. The resolution of photogrammetric measurements generally is inversely proportional to the field-of-view. Thus it is possible to increase resolution at the expense of limited field-of-view by using longer focal length lenses to zoom in on the outboard portion of the wing near the tip. However, once this is done the fuselage is no longer in the field of view to serve as a reference in order to remove the sting deflection component from the wing deflection. Thus, without fuselage deflection data, deflection measurements at various semispan locations will contain this sting deflection component as well as the wing bending. If wing bending is desired while maintaining the high resolution for wing twist with a limited the field-of-view, then either calculated values for sting deflection must be used or a second camera will be required to view the fuselage in order to measure the sting deflection to subtract from the measured bending on the wing.

Wing Twist Uncertainty Requirements?

AOA of balance	**$\Rightarrow$**	**Wing Twist**
0.01°	**?**	**0.05°**

The uncertainty requirements for the measurement of wing twist caused by aerodynamic loads are unresolved. It has been suggested that the desired uncertainty for wing twist which corresponds to an uncertainty of 0.01° for the model pitch angle is of the order of 0.05°, not 0.01°. In other words, an uncertainty of the order of 0.05° in wing twist is thought to have about the same magnitude effect on drag measurements as 0.01° uncertainty in model pitch angle. A sensitivity study of the effects of wing twist and bending on CFD solutions will aid in uncertainty analyses and can impact future test technique developments.

Technique

- **Single view photogrammetry**
- **Wind-off polar as reference**
- **Change in local AOA on wing**
- **Easier to automate**

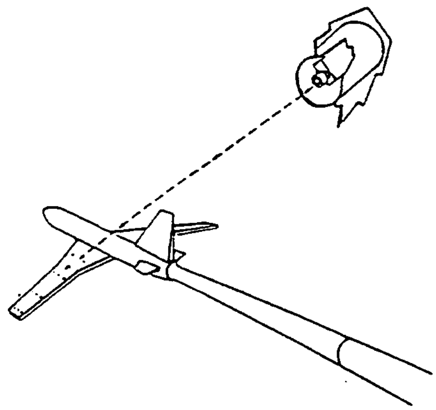
The optical technique used to determine wing twist data is based upon the recording and analysis of digitized video images. A video signal from a standard RS-170 solid state camera with 752 horizontal by 240 vertical pixels per field is routed to a frame grabber controlled by a Pentium 90-MHz PC which records one second or more of digitized video images into the frame grabber memory. Several of the digitized images are then analyzed in order to reduce the effects of dynamic yaw. It currently takes approximately one second per digitized image to automatically determine the image coordinates of three rows of wing targets. The charge-coupled device (CCD) video camera used for wing twist measurements at the NTF has an adjustable field integration time in order to reduce the effects of dynamics on image recording. A 10 to 100 mm focal length remote zoom lens is currently used for imaging. NASA TM 110229, published in Feb. 1996, presents the history of model deformation development at the NTF and describes the non-automated measurement technique used until recently at the NTF. A report on the automation of the technique will be presented at the Ground Testing Conference at New Orleans in June, 1996. Considerations when calibrating zoom lenses for wind tunnel use are discussed in SPIE Proceedings 2598 pp. 19 - 33, Oct. 1995.

Limitations and Problems

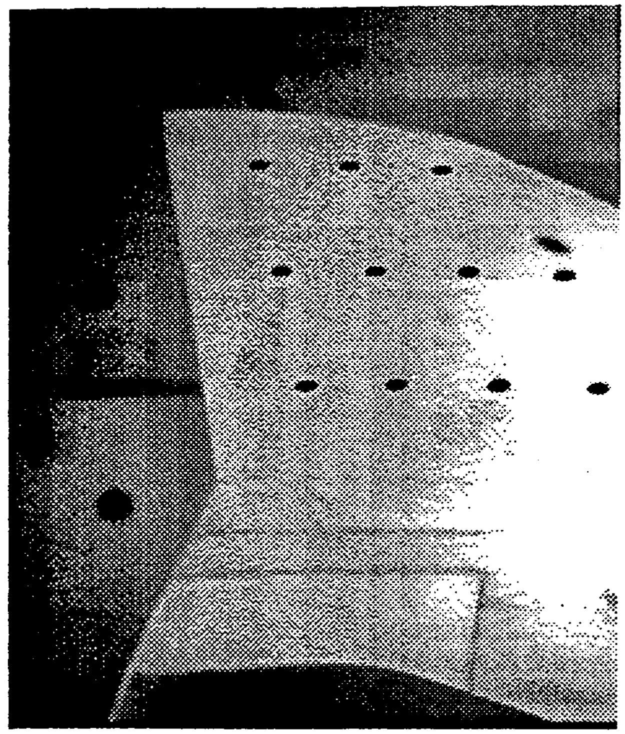
- **One coordinate must be known (spanwise)**
- **NOT 3D measurement**
- **Alpha sweeps only**
- **Wing targets**

Wing twist measurement error can occur due to errors in the camera position and pointing angles used to determine the *X* and *Z* coordinates. Pre-test calibration errors can also contribute to wing twist error if, for instance, incorrect lens distortion or frame grabber affinity corrections are used. Also note that errors in wind-off reference angle and wind-on angle will contribute to the error in the wing twist angle although generally the expected error in twist due to the wind-off pitch angle is much smaller than the error due to the wind-on angle. The *Y* coordinate, assumed to be known for the single camera solution, is constant and well-behaved for ambient wind-off pitch sweeps. This is verified by independent measurements in the test section as well as by the single camera technique, which typically has an rms error of 0.03° or less when compared to the onboard inertial angle sensor under wind-off ambient conditions. However, *Y* is not constant during wind-on conditions due to model yaw dynamics and wing bending. This variation in *Y* contributes to the precision error. As long as the image locations are not too far separated, the errors in *X* and *Z* will be similar and will tend to partially cancel. Wing bending causes the *Y* coordinate of wing targets to decrease which also causes a bias error in the computation of *X* and *Z*. This error partially cancels since targets at a given semispan location will experience similar *Y* shifts due to bending.

NTF Camera Location and View



Camera location



Video image

At the NTF the CCD camera is mounted in a protective housing in the test section sidewall. The camera looks over the fuselage at one of the wings of the model. Since perspective causes the images to be foreshortened in the vertical direction, the camera is rotated 90° so that the flow direction is vertical on the image plane in order to more nearly match the number of pixels vertically and horizontally across a target image. The protective housing is equipped with insulation and sheath heaters to maintain camera temperature. The housing is pressure rated to greater than 9 atm. In order to prevent frost, air heated by an inline heater flows to a purge ring with a number of holes to direct the heated air over the inside surface of the one inch thick fused silica window viewport. A purge air vent to atmosphere maintains the camera housing pressure at approximately 1 atm. Retroreflective tape targets have been used at the TDT and UPWT. In the past at the NTF, circular targets were applied to the wing surface with a Sharpie® marking pen. More recently (early 1996), a polished paint technique has been used at the NTF to produce high contrast targets. Initial X and Y coordinates of the targets are determined from pressure tap and other reference locations on the wing. The Z coordinates are estimated from cross-sectional drawings of the wing.

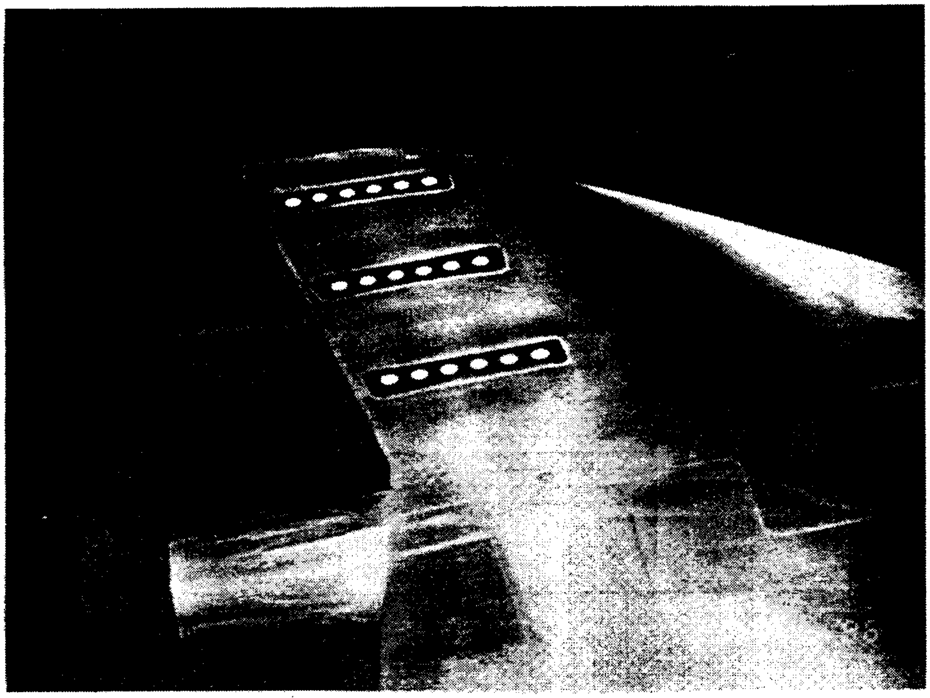
Recommendations

Emphasis be placed on developing high contrast, permanent, nondisturbing, optical targets for new and existing models at NTF

Emphasis be placed on determining the effects of wing target step height and surface roughness on aerodynamic data at the NTF

Innovations are sought to obtain high contrast, durable wing targets which do not exceed the surface finish requirements at the NTF. The surface finish of models at the NTF can approach 10 microinches or better, resulting in a "mirror like" surface. Thus images of the wing surface may also contain additional artifacts produced by reflections of a wall or ceiling. In order to successfully automate the wing twist measurement at the NTF high contrast targets are needed which do not exceed the surface finish requirements or unintentionally trip the flow. These targets should be flat-white solid-filled circles on a flat-black background or the opposite contrast. Sharpie® marking pen black targets are neither high contrast nor durable. In addition, some customers of the facility would prefer not to apply the targets due to uncertainty about the effects of the targets on aerodynamic performance; however, results to date do not indicate a measurable adverse effect. Targets applied by a chemical etching technique would be durable, but of low contrast. Gun bluing could also produce durable targets on at least some of the materials used for models at the NTF, but would still produce low contrast targets and have the additional problem of being a "controlled rusting process". Ideas for a suitable target application method at the NTF are solicited.

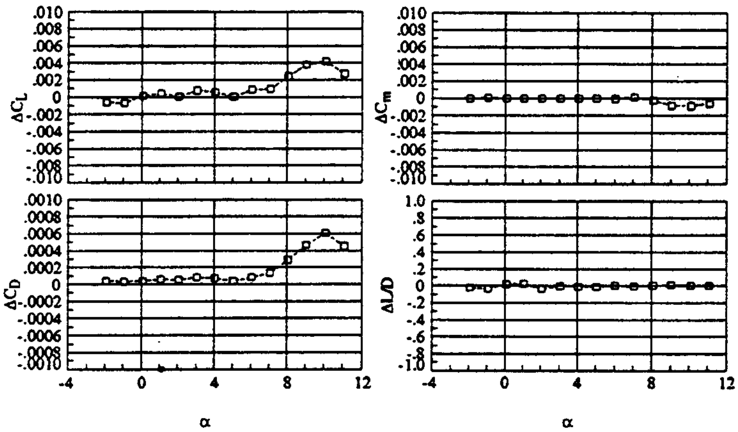
Polished Paint Targets at the NTF



A polished paint technique for applying high contrast targets suitable for cryogenic operation has been developed and was applied on the outboard panel for two configurations of the 2.2% HSR Reference H model recently (Feb. 1996) tested at the NTF (Test 78). The two configurations were the baseline wing with no flap deflection and the transonic wing with 10° and 3° flaps. This development of high contrast targets enabled automated wing twist measurements to be made for the first time at the NTF. Initial results are very encouraging and led to the decision to apply the same type targets on the wing of a subsonic transport model during the NTF test immediately following the HSR test.

Model Deformation Target Effect

- Preliminary Data from NTF078: Baseline Config.
  M = 0.90, Rn = 10.24e6, q = 967 psf
  Δ = targets on - targets off

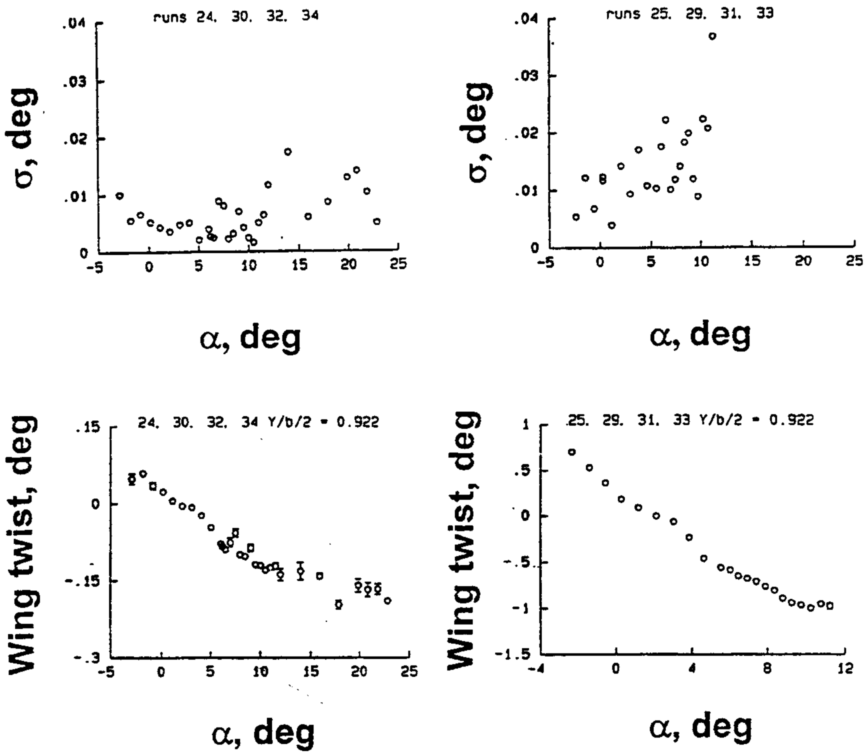


This figure shows the effect of the new high constrast, painted targets on the aerodynamic data. A set of 4 polars, plus 1 inverted polar, was run for both the target on and target off conditions at low Reynolds number in the air mode of operation. The data shown is the difference between curve fits of the data at selected angles-of-attack. Lift and drag coefficent data indicate a negligible effect at low angle-of-attack, but show an increasing effect beyond $\alpha = 8$ deg. Examination of the raw data indicate that the curve fits may have slightly biased the differences (order of one drag count high) at high angles-of-attack. In addition, data repeatability at the higher angles was on the order of ± 2 drag counts. Thus, it is not clear that the differences shown in the figure are significant. The effect on pitching-moment and lift-to-drag ratio is negligible, as was the effect of the lateral/directional coefficients (recall the targets were installed on the left outboard wing panel only).

Further work is required to fully quantify the target effect on the aerodynamics data.

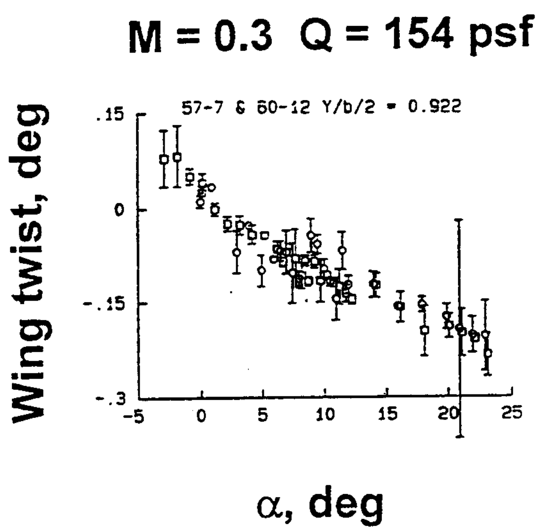
Run-to-Run Repeatability at the NTF

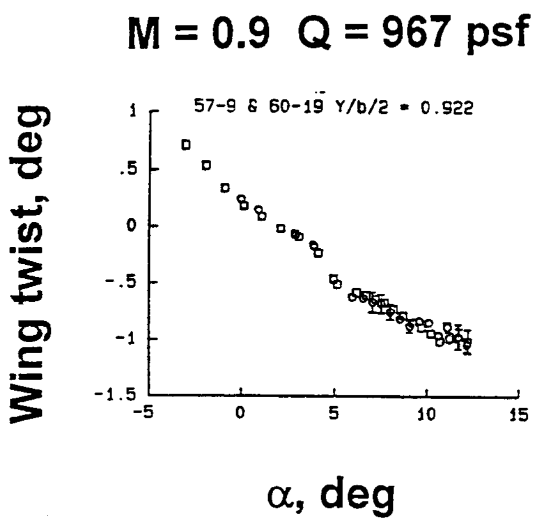
M = 0.3 Q = 153 psf **M = 0.9 Q = 965 psf**



Same day, run-to-run repeatabilities of the video wing twist technique for an HSR model during air runs are presented for Mach number of 0.3 and dynamic pressure of 153 psf on the left and $M = 0.9$ and $Q = 965$ psf on the right for a normalized semispan of 0.922. Data for semispan stations at 0.778 and 0.635 behaved similarly, but with correspondingly less wing twist. The error bars (which are plotted if greater than the symbol size) represent plus and minus one standard deviation of the four repeats at each Alpha. The mean standard deviation in twist angle for repeat points was less that 0.02° in air mode with a worse case standard deviation at the higher Mach number equal to less than 0.04°. Note that any error and variability in the onboard angle of attack for wind-on alpha or wind-off reference alpha will be added to the measured twist value.

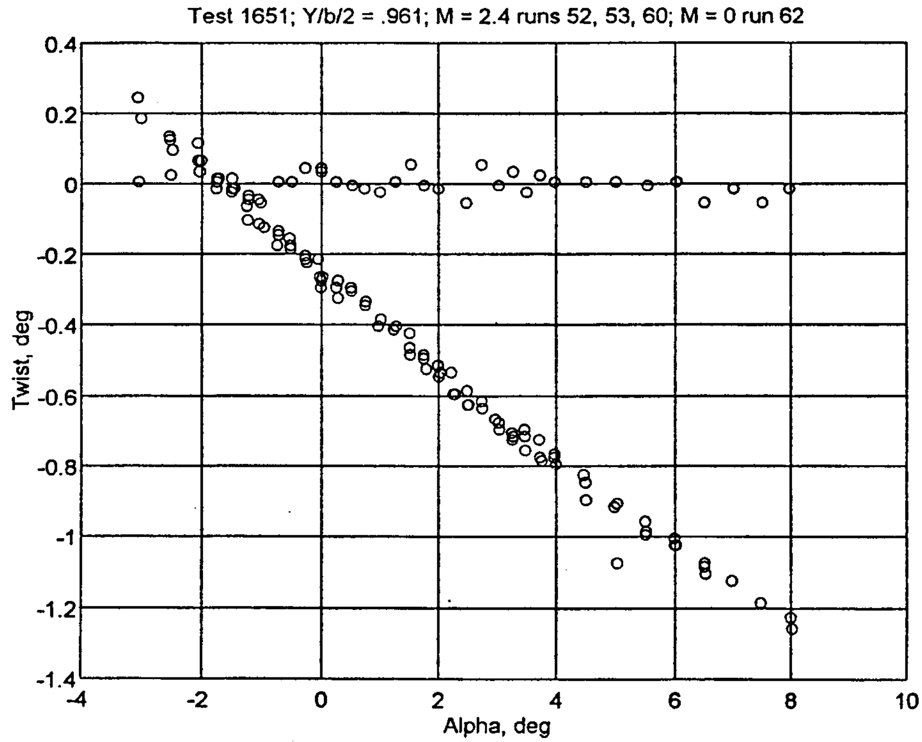
Test-to-Test Repeatability at the NTF





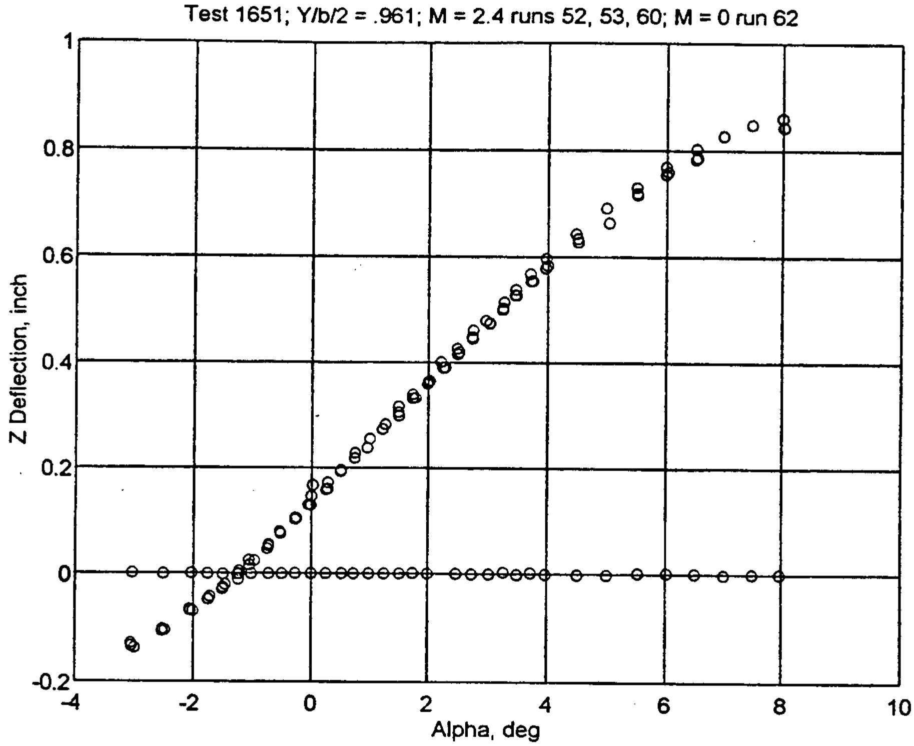
Comparisons of repeat runs from two HSR tests at the NTF (Tests 57 and 60) in air mode separated by over five months are presented above. Data from the two tests are represented by different symbols. The error bars represent plus and minus one standard deviation as computed from the least squares conformal transformation used in the computation of wing twist. Linear interpolation was used to account for differences in model pitch angle setpoint between the tests. For the plot to the left the Mach number was 0.3 and the dynamic pressure was 154 psf. For the plot to the right the Mach number was 0.9 and the dynamic pressure was 967 psf. Note how deviations from linearity repeat from test to test for the 967 psf data. The mean differences between the two tests are less than 0.03° with a worst case disagreement of 0.24° at alpha = 24° . For alpha's below 20°, the worst case disagreement is 0.05°.

Unitary Test 1651 Wing Twist



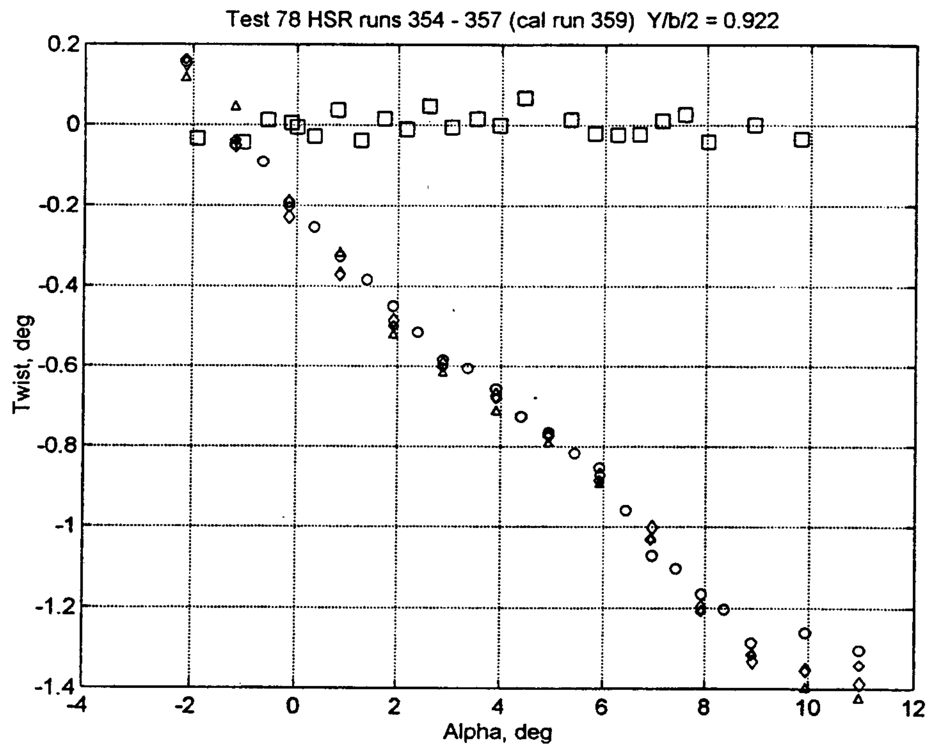
The wing twist data plotted above were recorded at the Langley Unitary Plan Wind Tunnel Test Section #2 during HSR Test 1651 of the 1.675% scale HSR Reference H model. Wing twist and deflection data were recorded for three repeat runs at Mach number equal to 2.4. Data were taken at two semispan stations, *Y/b/2* = 0.845 and 0.961. Least squares curve fits to a wind-off run were used to establish an online calibration. Wind-off standard deviations when compared to *Alpha* were 0.0086° at *Y/b/2* = 0.845 and 0.031° for *Y/b/2* = 0.961. There were 7 targets at the 0.845 semispan location which occupied a larger portion of the field-of-view compared to the 4 targets at the 0.961 semispan location. Thus the 0.845 semispan had the better resolution. Worst case disagreement was 0.08° between the three runs, part of which may have been attributable to error in *Alpha* since *Alpha* is subtracted in the computation of wing twist. Note that the *Alpha* for no twist is near -1.7°, in good agreement to the expected value. These successful results at UPWT with a temporary system led to the decision to procure a dedicated system for that facility. The procurement is currently underway.

Unitary Test 1651 Wing Deflection



The deflection of the 0.961 semispan row of targets is given above for HSR Test 1651 at the Unitary Plan Wind Tunnel Test Section #2 at a Mach number of 2.4. Deflection due to sting bending is included in the above plot. Note that for these tests the model shifted longitudinally several inches as the pitch was varied, further complicating the interpretation of deflection in the vertical direction. The *Z* deflection values above are computed as the difference in the vertical direction between wind-off and wind-on at a normalized chord location *X/C* = 0.5. The wind-off values of deflection were fitted to a 4th order polynomial before subtraction. The standard deviations of the wind-off residuals after the fit were 0.0011 inch for *Y/b/2* = .845 and 0.0012 inch for *Y/b/2* = 0.961. Worst case disagreement for the three runs during the Mach 2.4 flow was 0.01 inch.

NTF Test 78



The change in wing twist due to aerodynamic load is presented in the above plot as a function of model angle-of-attack, *alpha* for four repeat runs during Test 78 of the transonic configuration of the HSR Reference H model at the NTF. For these runs the Mach number was 0.9, the dynamic pressure was 1005 psf, the total temperature was -184° F, and the total pressure was 20.8 psi. Data is presented at the 0.922 semispan location. Data were also taken at the 0.778 and 0.635 semispan locations. The square symbols represent the wind-off reference polar used to calibrate the angle measurement system at the same tunnel temperature and pressure as for the flow runs. The angle data from four images at each point were averaged to determine the change in wing test

Summary

- Model Deformation at 3 LaRC Facilities
  (Feasibility study for 4th)
- NTF instrumentation issues
- Wing twist and bending
- NTF and UPWT data presented

Model deformation measurements have been made at three NASA Langley Research Center facilities: the National Transonic Facility (NTF), the Transonic Dynamics Tunnel, and the Langley Unitary Plan Wind Tunnel (UPWT). The development of a model deformation system at the NTF has been especially challenging. Some of the instrumentation concerns at the NTF have been presented. The emphasis in the development of a model deformation capability has been on the accurate and repeatable measurement of the change in wing twist due to aerodynamic load in a manner suitable for routine wind tunnel testing. The uncertainty requirements for model deformation, specifically the change in wing twist, remain an open issue. Model deformation examples from the NTF and Langley UPWT have been presented.