

Videometric applications in wind tunnels

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ABSTRACT

Videometric measurements in wind tunnels can be very challenging due to the limited optical access, model dynamics, optical path variability during testing, large range of temperature and pressure, hostile environment, and the requirements for high productivity and large amounts of data on a daily basis. Other complications for wind tunnel testing include the model support mechanism and stringent surface finish requirements for the models in order to maintain aerodynamic fidelity. For these reasons nontraditional photogrammetric techniques and procedures sometimes must be employed. In this paper several such applications are discussed for wind tunnels which include test conditions with Mach numbers from low speed to hypersonic, pressures from less than an atmosphere to nearly seven atmospheres, and temperatures from cryogenic to above room temperature. Several of the wind tunnel facilities are continuous flow while one is a short duration blow-down facility. Videometric techniques and calibration procedures developed to measure angle of attack, the change in wing twist and bending induced by aerodynamic load, and the effects of varying model injection rates are described. Some advantages and disadvantages of these techniques are given and comparisons are made with non-optical and more traditional video photogrammetric techniques.

Keywords: wind tunnels, angle measurements, displacement measurements, photogrammetry, model deformation, angle-of-attack, twist measurements, bending measurements, sting bending

1. INTRODUCTION

1.1. Model attitude

The measurement of model attitude is a critical measurement in any wind tunnel test¹. The pitch angle of a balance that rotates with the model must be known in order to properly resolve balance force components. The predominant instrument used for model attitude is an inertial sensor, the servo accelerometer. However, dynamic response problems encountered with inertial model attitude sensors can limit their effectiveness as angle measurement devices when located in wind tunnel models. Inertial sensors cannot distinguish between the gravity vector and the centrifugal accelerations associated with wind tunnel model system vibration, thus a model attitude measurement bias error can occur. The dynamic problems associated with inertial devices have been studied² and several schemes^{2,3} have been proposed and investigated to correct for this bias error.

Inertial sensors have other problems besides the possible bias errors caused by model dynamics. These problems include: (1) their fragile nature, (2) requirements for special handling, (3) requirements for multiple accelerometers for the measurement of pitch and roll, and (4) stringent space and wiring requirements in the model fuselage. For these reasons (in addition to the possibility of bias errors caused by model dynamics) alternative methods for measuring AOA have been sought. Much of the interest has been in optical techniques that are generally assumed to be immune from the dynamic problems inherent in inertial devices. However, even though optical techniques may not be theoretically affected by dynamics in the same manner as inertial sensors, experimental implementation of optical techniques may lead to errors due to dynamics caused by such things as variations in irradiance. Thus it is recommended that dynamic tests be conducted on any potential AOA measurement technique, including optical techniques².

It should be noted that inertial model attitude sensors have served the aerodynamic ground testing community well for many

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years and it is not expected that they will be completely replaced in the near term. In fact, several of the optical techniques rely on an inertial device (either onboard the model or on the model support mechanism) for calibration with wind off due to the high reliability and low uncertainty of the inertial devices when dynamics are limited.

A number of optical techniques have been investigated for measuring AOA⁴⁻⁷, but none of these appear practical for both air and cryogenic runs at the National Transonic Facility (NTF) located at NASA Langley. Some of the problems with these and other optical techniques are that lasers are often used as light sources that require special considerations for packaging in a harsh wind tunnel environment (especially a cryogenic high-pressure environment such as at the NTF). Special sensors (some requiring wiring) may be needed in the model fuselage. Some of these sensors may require windows in the fuselage, which need special protection during model preparation. Major advantages of videometric techniques compared to other optical techniques are that a laser is not required and a sensor does not need to be placed in the model fuselage. A problem common to most of the optical techniques (including the optical technique discussed here) is that fog in the test section may attenuate light to the point where the optical angle measuring system may not work at all, whereas the onboard inertial sensor will operate independently of tunnel fog. It is interesting that fog is a bigger problem in conventional transonic tunnels (such as the Langley 16-Foot Tunnel) than in cryogenic tunnels such as the NTF.

One disadvantage of the video method is the potential sensitivity of the technique to the location on the image plane of the line or edge from which the angle measurements are determined. This sensitivity to image location can be partially compensated by suitable distortion calibrations. Another disadvantage is that the technique does not function as an angle transducer to produce a voltage output proportional to angle as is common to most of the other optical techniques and inertial sensors. Wind tunnel data acquisition systems are generally set up to handle such transducers in a standard manner. To measure angle with the video technique, computations on the gray scale of digital images is required. These computations, while amenable to automation for fixed geometries and high contrast, make it difficult to automate the process to include variable geometry, especially if high contrast can not be maintained. In addition, camera alignment stability, practical in-place facility calibration, and various assumptions made in the angle determination are all issues requiring further study. Further laboratory and tunnel tests are necessary to more completely characterize and develop the videometric technique so as not to impact wind tunnel productivity before it is suitable for routine use as the primary measurement of angle of attack.

1.2. Model deformation

Model deformation may be defined as the change in shape of a model (particularly the wings and control surfaces) under aerodynamic load in a wind tunnel. This change in the design geometry can cause differences between the acquired and expected wind tunnel results if the expected results are based upon rigid body assumptions. Differences can also occur between acquired wind tunnel data and computational predictions based upon rigid body assumptions. These differences can lengthen and degrade the aircraft design process. The measurement of model deformation has thus been of interest for over 20 years. The fundamental technique used to measure model deformation continues to be photogrammetry as was the case 20 years ago⁹, but today electronic imagers are used in place of film cameras. The rapid development of relatively low cost electronic imaging, driven largely by the consumer video market, coupled with improvements in low cost computing have enabled the application of video photogrammetric techniques to a number of different types of measurement problems, including model deformation. However, turnkey video photogrammetry systems are generally not suitable for incorporation into a wind tunnel data acquisition system because of the user interaction required. In addition, limited view ports, illumination, and targeting options often contribute to the requirement for custom measurement systems for large wind tunnels.

The history of the development of a model deformation measurement capability for the National Transonic Facility is presented in reference 10 which includes the rationale for the current single camera, single view photogrammetric technique with emphasis on the measurement of the change of wing twist due to aerodynamic load. Examples of the measurement of wing twist in non-automated mode along with error considerations are also presented in reference 10. A description of the automation of the videometric model deformation technique, experimental procedure and data reduction, description of software, and targeting considerations are given in reference 11.

A major consideration in the recent development of an automated test technique for model deformation was that the productivity of wind tunnel testing should not be appreciably reduced while providing useful and accurate deformation information. The determination of the change in wing twist due to aerodynamic loading is the primary concern, while wing deflection (bending) is of secondary importance. In addition, angular measurements such as model pitch are common in wind tunnel testing, whereas deflection measurements are not. Also the measurement of the change in pitch angle at various

stations on the wing under wind-off conditions can be used for in situ calibration. Thus 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. Less emphasis has been placed on the measurement of wing bending.

2. EXPERIMENTAL TECHNIQUE

The basic hardware for the videometric techniques includes a CCD camera, frame grabber, and computer. A 2/3 inch format CCD camera with variable integration time and 752H X 240V pixels per image field has been found to work well. A zoom lens with focal length of 10 to 100 mm is convenient for wind tunnel tests. Additional considerations for the calibration of zoom lenses can be found in reference 12. A PC resident frame grabber with large (up to 64 Mbytes) onboard memory is useful in order to record and analyze several seconds of angle and displacement data. A reduction in the number of pixels per image field stored to grabber memory allows even longer time sequences to be analyzed if needed. This capability was found useful, for example, in the study of model injection at a hypersonic facility. The data acquisition and reduction program is written in C. Data acquisition time is typically one second. Data reduction time is typically a few seconds for 15 image fields recorded over one second for model deformation measurements. The edge detection used for model attitude is faster than the target centroiding used for model deformation so that all 60 images recorded over one second can be analyzed in just a few seconds. An additional quick plot routine and separate data reduction program are available to examine the angle and displacement data as a function of time for selected regions of the data.

2.1. Model attitude

The optical technique used to determine model attitude is based upon the recording and analysis of digitized video images. The basic measurement is the determination of the slope angle and intercept of an edge in the field of view of the camera. The slope angle and intercept are determined from a least squares adjustment of up to 25 equally spaced measured edge locations per image. The camera is oriented such that the edge is nearly vertical on the camera image plane when the model is leveled. This orientation significantly decreases the amount of time required for the image processing described below since the pixels are more naturally extracted from the frame grabber memory by horizontal rows.

The edge is found for a given row of pixels using the following procedure. Pixels along a row are tested to locate a region in which the difference in gray scale exceeds a preset threshold. The gray scale located several pixels in front of this region is then stored. The remaining pixels along the row are then tested for a difference in gray scale that is less than 1/2 of the threshold. The gray scale several pixels past this region is considered to be past the edge. This gray scale is added to the previously stored gray scale and the result halved to establish a reference gray scale considered to be located at the edge. The estimated pixel location of the edge is then found to subpixel resolution by gray scale interpolation between pixels closest in value to the reference gray scale. A predetermined number of rows are then skipped and the procedure repeated until the bottom of the image field is reached.

Once an image field is completed, a linear least squares fit is made to the set of horizontal and vertical edge locations which have been properly scaled to compensate for differences between the horizontal and vertical pixel spacings. The slope angles and intercepts (in pixels) for each field image are then stored in a single file for each data point acquired. This data can be plotted and analyzed to investigate the dynamic behavior of the angle and slope data. In addition, the mean slope angle and intercept as well as standard deviation, minimum, and maximum are stored in an append file which has one row of mean data per tunnel point. Tunnel data such as date, time, Mach number, alpha, etc. are read (via automatic ftp) from a file overwritten on a workstation by the tunnel data acquisition system each time a tunnel data point is taken. Tunnel data can also be retrieved by RS-232. Once retrieved, the tunnel data is merged into the output append file. Once the angle and slope calculations for each field have been completed and the data stored to file, the mean slope angle and standard deviation are displayed. The data system is then ready for the next contact closure to initiate data taking. The display also contains a live readout of angle while the system is in a ready to take data state.

Options for the angle measurement system include the following: 1) set slope and offset corrections for the angle, 2) zero the angle reading interactively, 3) process a previously digitized image, 4) display live gray scale image data for pixels near the edge, 5) select sign of slope of edge, 6) select right-to-left or left-to-right pixel scan, 7) set number of image fields to be analyzed per data point, 8) set image data recording rate (up to 60 Hz), 9) set the horizontal and vertical pixel size in mm, and 10) set the number of horizontal and vertical pixels to be used. The ability to process a previously digitized image and display live gray scale image data for pixels near the edge are useful during initial checkout or troubleshooting during tunnel runs. The pixel scan direction is selected so as to approach the edge from the side with the least extraneous gray scale

structure in order not to confuse the edge detection.

Tunnel tests have been conducted which include edges defined by one of the following: a glint along the edge of the fuselage, a relatively high gray scale model edge in contrast to a black background, a dimly lit model contrasted against a white background, or retroreflective tape edges illuminated by a fiber optic ring lamp mounted on the camera lens. The first three edge illumination schemes suffer from their dependence on normal test section lighting since lighting requirements for AOA may differ from the lighting requirements for general model surveillance. For very critical surveillance the wind tunnel Test Director may find it necessary to re-adjust the test section lighting which might invalidate the video calibration or cause loss of signal. The retroreflective tape is not ideal since the tape must be placed on the model. The tape thickness of 0.004 inch and increased surface roughness may not be suitable for models at the NTF where surface finish requirements are very stringent.

A background-illuminated technique has been found most useful to achieve a very high contrast edge while remaining independent of the test section lighting. A standard ground glass viewing screen back illuminated with an incandescent light bulb serves as a relatively inexpensive background. A fiber optic illuminated faceplate is a higher cost option, but is more uniform in illumination level across the plate. The high illumination level from the ground glass or fiber optic faceplate allows the camera lens aperture to be stopped down significantly so that the model edge appears black in the image plane and the test section or room lights do not affect the video signal. A major disadvantage of the back illuminated technique is that access to windows on both sides of the test section are required, or part of the test section wall in the field of view must be replaced with the back illuminated surface. However, the back illuminated technique, if possible, is the preferred method to obtain high contrast edges that are nearly immune to test section or room lighting. Encouraging preliminary tests have been conducted at the NASA Langley 20-Inch Mach 6 CF₄ Tunnel using background illumination.

2.2. Model deformation

Targets must be placed on the wing at the semispan locations where change in wing twist and bending are required. The Y coordinates of the targets in the spanwise direction are determined from pressure tap and other reference locations on the wing to be used in the computation of X in the streamwise and Z in the vertical direction. High contrast targets are required on the wing in order for the image processing routines to automatically locate the targets reliably, without ambiguity, and with no user interaction. These wing targets are either white diffuse circular targets on a dark background, or ideally, retroreflective tape targets such as have been used at the NASA Langley Transonic Dynamics Tunnel and the Unitary Plan Wind Tunnel. A light source placed near the camera will yield a very high contrast image when the retroreflective tape targets are used.

Retroreflective tape targets have not yet been used at the NTF due to difficulties in locating a light source sufficiently close to the camera. Instead, a polished paint technique has been used at the NTF to produce high contrast white dot targets allowing the first automated measurements of wing twist at the facility. A black background surrounding the white targets is produced by reflection of a black test section wall from the highly reflective wing surface. A typical target set at a given semispan station consists of a row of 4 white circular targets with a diameter of 8 mm aligned along the streamwise direction. Target rows are generally located at three or more semispan stations along the wing in addition to the body. The body targets are used to determine the pitch angle for comparison to the onboard inertial sensor. In cases where the two results differ and model dynamics are low enough not to perturb the results from the inertial sensor, the body data from the videometric system can be used for correction of data along the wing. If model dynamics are high, the videometric body results can be used as an alternate source for the angle of attack measurement itself.

2.3. Calibration

The initial pre-test calibration procedure for the videometric techniques determines those camera parameters necessary for conversion from pixels to corrected image plane coordinates. The photogrammetric principal point is found using a laboratory laser illumination technique. The point of symmetry for distortion is determined in situ from the point of image symmetry of the zoom lens¹². In cases where the video camera cannot be taken back to the lab the principal point is taken to coincide with the point of symmetry for distortion. The need for extensive camera calibration is lessened somewhat by on-line calibration using the model pitch angle for wind-off reference at the tunnel total temperature and pressure test conditions. The pointing angles and location of the camera in the tunnel coordinate system are determined at the start of the test by photogrammetric resection on a target plate which is aligned to the horizontal X, Y plane of the tunnel. The target plate consists of a flat black plate with an array of white targets with known locations. The X -axis of the calibration plate is aligned parallel to the body axis by contact with a leveled V-block placed on the body. The V-block also serves as a convenient way to establish the distance of the calibration plate zero Y -reference from the body axis. The target plate is

translated a known amount along an optical rail to several Y locations where resections are made. Provided the alignment is correct, the three pointing angles and X and Z of the camera will be nearly equal at each location of the plate whereas the Y value for the camera will follow the change in location. A technique is then used to determine the photogrammetric principal distance that causes best agreement with the changing Y values of the target plate if necessary. The technique for determining the principal distance is based on the next section.

2.3.1 Determination of photogrammetric principal point

The collinearity equations can be expressed for a positive image as

$$\begin{aligned} x &= -c f_x \\ y &= -c f_y \end{aligned} \quad (1)$$

where x, y are the image plane coordinates corrected for distortion and centered at the photogrammetric principal point. The variables f_x and f_y are functions of the Euler angles ω, ϕ , and κ , the location of the perspective center, X_o, Y_o, Z_o and the location of the object point, X, Y, Z . If the object field is a plane centered at $(0, 0, 0)$ and parallel to the image plane so that the Euler angles are zero and the camera perspective center located at $(0, 0, Z_o)$, the collinearity equations reduce to

$$\begin{aligned} x &= c X / Z_o \\ y &= c Y / Z_o \end{aligned} \quad (2)$$

If an incorrect principal distance, c_o , is used during resection, a corresponding incorrect value will be found for Z_o . If the incorrect value for Z_o found by resection is designated by Z_r , then the collinearity equations (with incorrect c_o) become

$$\begin{aligned} x &= c_o X / Z_r \\ y &= c_o Y / Z_r \end{aligned} \quad (3)$$

Thus, the correct value for c can be expressed as

$$c = c_o Z_o / Z_r \quad (4)$$

The variable Z_r is found from the resection, but Z_o , the correct value, is unknown. If the calibration plate is displaced in the Z direction a known amount then the *change* in Z_o , designated as ΔZ_o , is known and can be used to compute the true value of c with the corresponding change in Z_r , designated as ΔZ_r , from resection based on the assumed value of c_o with

$$c = c_o \Delta Z_o / \Delta Z_r \quad (5)$$

The true principal distance c can be computed with least squares if the calibration plate is displaced to different values of Z and the resection computed. Once c is determined, the resections with the correct value of c are recomputed for the various Z displacements to yield mean values for the exterior orientation.

Once the three Euler angles and position of the camera are established relative to the tunnel coordinate system, measurements can then be made on the target plate for an in situ check of the technique by comparing measured and known Z values. Providing the Z value determinations are reasonable, a pitch polar can then be taken with wind-off to ensure that the change in pitch angles on the wing measured by the automated system track with the onboard accelerometer.

An alternate technique to the above for determining the pointing angles and location of the camera in the tunnel coordinate system is by photogrammetric resection of a wind-off reference run. A known set of targets for resection are established by merging wind-off points at several angles into a single reference target field based on knowledge of the center of rotation and the rotation angle from the onboard accelerometer.

The final calibration step requires a wind-off pitch sweep at run temperature and pressure over the range of angles expected during the subsequent wind-on testing. A wind-off polar in the middle and at the conclusion of a set of runs is helpful to verify system stability, especially at the NTF during cryogenic operation.

3. WIND TUNNEL MEASUREMENTS

The measurement of angle to 0.01° or better in a laboratory environment is not particularly difficult for any number of different optical techniques. For example, evaluation tests with the videometric angle measurement systems have been conducted at the Langley angle calibration lab¹ where angles can be set to an accuracy of 0.0003° . These laboratory tests established that under best case controlled conditions the precision of the technique is typically 0.003° rms and the accuracy when compared to the standard is typically 0.01° rms over $\pm 30^\circ$. However, the measurement of angle of attack to 0.01° in an operating wind tunnel is by no means a relatively easy task due to the many operational constraints and limitations of production wind tunnel testing. Techniques that work well in the lab may not be suitable at all for production wind tunnel testing. In addition, a technique suitable for one facility may not be appropriate for another. Thus experience in actual wind tunnel testing is critical in the early development of model attitude measurement techniques. This does not mean that laboratory investigations are not needed, but rather that test technique development will be a necessarily long iterative process with both laboratory and wind tunnel testing. That way one can appreciate and work to develop strategies to overcome the many constraints and limitations of wind tunnel testing. Attention to detail is critical in test technique development as evidenced by the long and very productive history of the development of inertial devices for model attitude¹. The research required to develop a test technique to be used routinely as a primary wind tunnel measurement system is often more challenging, and can actually be more rewarding, than the laboratory development of new test techniques.

Videometric pitch angle measurements have been made at several NASA Langley facilities: the National Transonic Facility, the 20-Inch Mach 6 CF₄ Tunnel, and the 14- by 22-Foot Subsonic Tunnel. These tests were conducted to evaluate and gain experience with the optical system under actual wind tunnels conditions. Whenever possible the videometric tests were conducted on a nearly non-interference basis and the video system was not used for the primary measurement of angle of attack. Videometric model deformation measurements have been made at the following Langley facilities: the NTF, the Transonic Dynamics Tunnel, and the Unitary Plan Wind Tunnel. In addition, measurements have been made at the NASA Ames 12-Foot Pressure Tunnel in California. A dedicated videometric system for model deformation measurements is currently under development for the Langley 16-Foot Transonic Wind Tunnel as well. Examples of videometric measurements at several Langley facilities are presented next.

3.1 National Transonic Facility

The National Transonic Facility (NTF) is a fan-driven, closed circuit, continuous-flow pressurized wind tunnel¹³. The 8.2 x 8.2 x 25-ft long test section has a slotted-wall configuration. The wind tunnel can operate in an elevated temperature mode up to $T = 140^\circ\text{F}$, normally using air, and in a cryogenic mode, using liquid nitrogen as a coolant, to obtain a test temperature range down to about -250°F . Thermal insulation inside the pressure shell minimizes energy consumption. The design total pressure range for the NTF is from 15 psia to 130 psia. The combination of pressure and cold test gas can provide a maximum Reynolds number of 120,000,000 at Mach 1.0, based on a chord length of 9.75 inches. These characteristics afford full-scale Reynolds number testing for a wide range of aircraft. Three types of investigations are possible: Reynolds number effects at constant Mach number and dynamic pressure; model aeroelastic effects at constant Reynolds number and Mach number; and Mach number effects at constant dynamic pressure and Reynolds number. The constraints imposed by operation in a high-pressure environment over such a wide range of temperatures have had a significant impact on the continuing development, improvement, and optimization of instrumentation at the facility.

A major instrumentation challenge at the National Transonic Facility is the requirement to make measurements over the wide range of temperature from 140°F down to -250°F . To make AOA measurements over this large temperature range an onboard accelerometer in a heated temperature controlled package is used as the primary measuring system for alpha testing. An accelerometer located on the arcsector plus sting bending angular corrections serves as a check when the onboard accelerometer is primary and often replaces the onboard accelerometer as primary for alpha/beta testing. When the videometric angle system is operational there are three angle measurement systems to compare to one another as advocated in reference 14. An example of the comparison of the three AOA measuring systems for a cryogenic run at Mach 0.9, a Q of 2700 PSF, and a temperature of -185°F is presented in fig. 1 as a function of the arcsector plus bending pitch angle. The video angle minus the arcsector and bending is indicated by *Vid - Arc*, the video minus onboard accelerometer is indicated by *Vid - Acc*, and the arcsector and bending minus the onboard accelerometer is indicated by *Arc - Acc*. For this test the video system viewed the front illuminated section of the model body edge contrasted against a test section wall painted black. A wind off alpha sweep was used to calibrate the video system at temperature. With wind off the onboard accelerometer and the arcsector plus bending pitch angles differed only by an offset of 0.01° so that the wind off calibrations of the video system with either angle set differed only by that offset. Note that for this data set the best agreement occurs

between the video and arcsector plus bending and that there is a trend in the *Arc - Acc* and *Vid - Acc* differences which indicates more scatter and bias error in the onboard pitch angle. Similar results are noted for a run at -250° F as shown in fig. 2. Note that this limited data set is for a single model/sting configuration and that normally one would expect the onboard accelerometer to be superior to the arcsector accelerometer plus sting bending except for cases where dynamics are excessive. These data sets illustrate the value of comparing three nearly independent angle measurement devices.

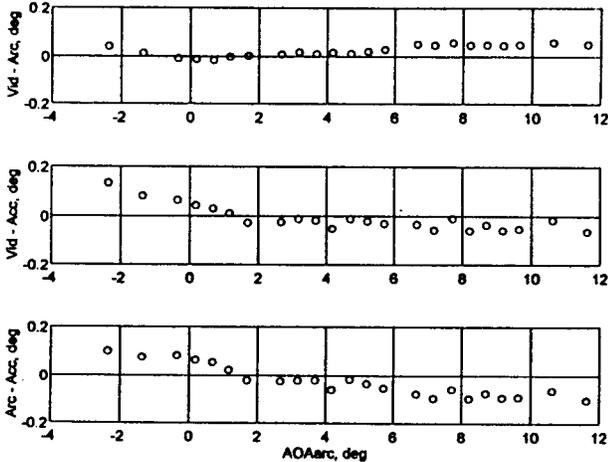


Fig. 1. Comparisons of three AOA measurements at Mach = 0.9, $Q = 2700$ PSF, and temperature of -185° F.

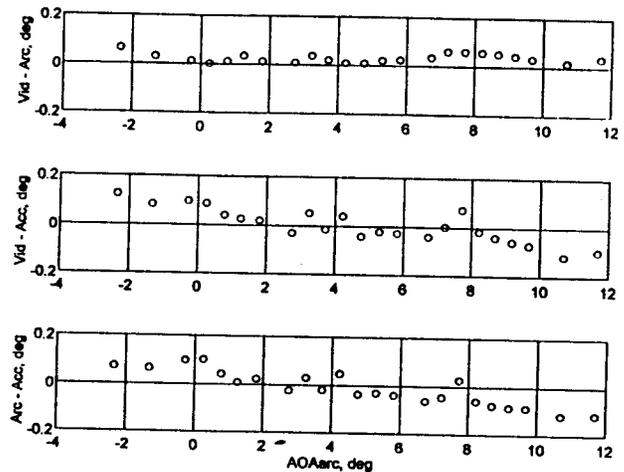


Fig. 2. Comparisons of three AOA measurements at Mach = 0.9, $Q = 2700$ PSF, and temperature of -250° F.

An example¹⁰ of the change in wing twist due to aerodynamic loading plotted as a function of angle of attack is presented in figure 3 for various dynamic pressures. The Mach number and total pressure were varied to give the desired dynamic pressure. The data were taken for a low aspect ratio research model in air mode at a normalized semispan equal to 0.922. The increase in washout (decrease in twist) as the angle of attack increases is characteristic of rearward swept wings. Videometric model deformation measurements have recently been used to calibrate and validate finite element methods (FEM) used to predict wing twist and bending under aerodynamic load for several advanced subsonic technology wind tunnel models¹⁵ as well as to provide aeroelastic data for several research models.

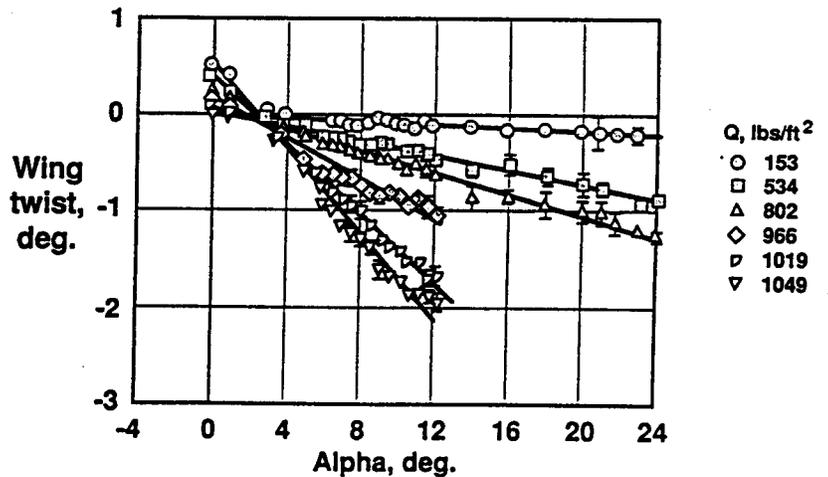


Fig. 3. Change in wing twist due to aerodynamic loading for air runs at varying dynamic pressures.

3.2 Transonic Dynamics Tunnel

The Langley Transonic Dynamics Tunnel (TDT) is a unique "national" facility that is used almost exclusively for performing aeroelastic research and for conducting flutter-clearance and other aeroelastic-verification tests of Department of Defense, industry, and NASA fixed-wing and rotary-wing flight vehicles and launch vehicles¹³. Semispan sidewall-mounted vehicles and full-span sting-mounted or cable-mounted models can be used. In addition, a rotorcraft test-bed is

available for rotor-blade loads research. The TDT is a continuous-flow, variable-pressure wind tunnel with a 16-ft by 16-ft test section. The tunnel uses either air or a heavy gas as the test medium and can operate at Mach numbers up to about 1.2 while obtaining Reynolds numbers per foot of approximately 3×10^6 in air and 10×10^6 in heavy gas.

The first automated videometric measurements of wing twist and bending at NASA Langley 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. A frame grabber with a large onboard memory of 64 Mbytes has been used to record and analyze up to 8 sec of video images per data point taken at a 60 Hz rate for dynamic studies. The system at the TDT has been used for a number of tests of semispan models, both rigid and flexible. Static loading tests have been conducted with the automated videometric system with agreement to 0.3 mm compared with dial gauges. Measurements have also been made on the Northrop Grumman Smart Wing that had variable twist and adaptive control surfaces to provide continuous wing contour and variable camber. In addition, the measurement system was adapted for displacement measurements during a preliminary test of a piezoelectric wafer being investigated to control aerodynamic surfaces. Fluorescent paint on the wafer edge illuminated by UV light sources provided a high contrast image suitable for automated measurements in a small-scale wind tunnel setup. Deflection measurements at a 30 Hz rate in bursts up to 1 minute (or at a 10 Hz rate for continuous operation) were possible with the modified automated measurement system.

3.3 Unitary Plan Wind Tunnel

The Langley Unitary Plan Wind Tunnel (UPWT) is a closed circuit, continuous-flow, variable-density tunnel with two 4-ft by 4-ft by 7-ft test sections¹³. One test section has a design Mach number range from 1.5 to 2.9, and the other has a Mach number range from 2.3 to 4.6. The tunnel has sliding-block-type nozzles that allow continuous variation in Mach number while the facility is in operation. The maximum Reynolds number per foot varies from 6×10^6 to 11×10^6 , depending on Mach number. Types of tests include force and moment, pressure distribution, jet effects, dynamic stability, and heat transfer. The videometric model deformation system at the UPWT has sufficient automation that facility personnel now fully operate the system, including calibration and validation, for selected tests in either test section. The measurement system has been used for aeroelastic studies to assess Mach number and Reynolds number effects in addition to comparisons of models with flapped and solid wings.

3.4 20-Inch Mach 6 CF₄ Tunnel

The 20-inch Mach 6 CF₄ Tunnel is part of the Hypersonic Facilities Complex¹³. The purpose of using the test gas CF₄ is to better simulate the real-gas effects on blunt bodies. At the 20-inch Mach 6 CF₄ Tunnel the model is vertically injected into the test section for 10 or so seconds and then retracted. The model injection can occur at several speeds and the angle of attack can be changed to up to three values while in the test section. Since models are too small for onboard inertial sensors, the angle of attack is typically measured with an inertial device placed on the baseplate of the strut mounting mechanism with wind off. Thus the angle of attack after the model is injected with wind on may differ from the initial value with wind off. Sting bending due to aerodynamic loading is another complication, particularly at high angles of attack. Loading calibrations are conducted and sting bending angle corrections are made based on these calibrations, but these corrections are subject to experimental error and the assumptions made in determining these corrections may not be entirely valid.

Tests have been conducted using the videometric angle measurement system in order to study sting bending and model injection with wind on and wind off¹⁶. Angle measurements were made on a small section of the model that was in the field of view of the camera when the model is fully injected into the test section. A back illuminated ground glass view screen was placed in the field of view of the camera to yield a very high contrast edge of the model. The video camera was reoriented for each run to allow for the large range of angles up to 50°. Wind off model injections before and after the wind on injection were used as reference to determine the change in angle of attack from wind off to wind on and also to study the dynamic behavior of the model. Fig. 4 presents comparison plots at Mach 6 for slow and medium speed model injection. Note the ringing when using medium speed injection and that the valid testing time (without ringing) is comparable for the two injection speeds.

The change in angle from the mean for the wind off and wind on model injections (Mach 6) are plotted for comparison in fig. 5 at 0.0° AOA. The mean AOA for the first wind off injection is used as reference and subtracted from the means of the wind on run and final wind off run. The sting bending due to aerodynamic loading is measured to be 0.02°, which is about the repeatability of wind off injections. Similar plots are presented (again at Mach 6) for an AOA of 50° in fig. 6. At 50° AOA the sting bending is determined to be positive 0.53°. A summary sting-bending plot for nine runs at Mach 6 is presented in fig. 7. A second order polynomial curvefit is superimposed. More detailed discussion of the sting bending measurements and the possible impact on sting bending calibration are available¹⁶.

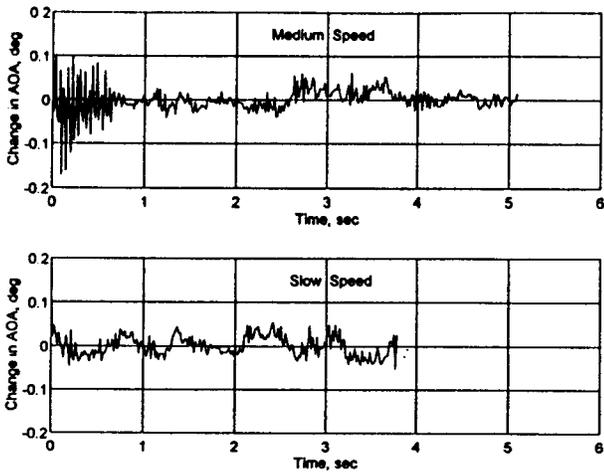


Fig. 4. Mach 6 comparison plots of slow and medium speed model injection.

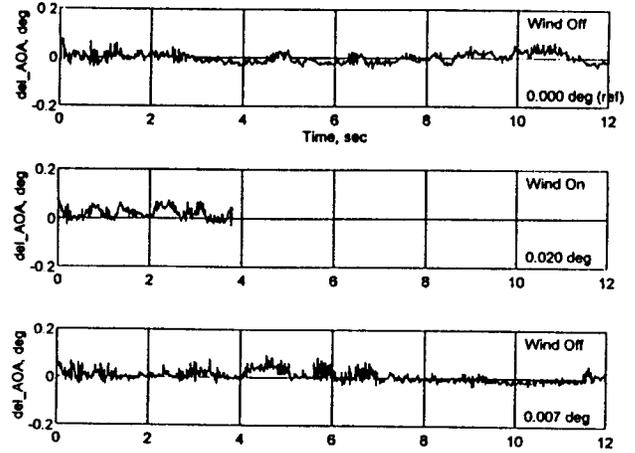


Fig. 5. Change in AOA from the mean for wind off and wind on (Mach 6) model injections at 0° AOA.

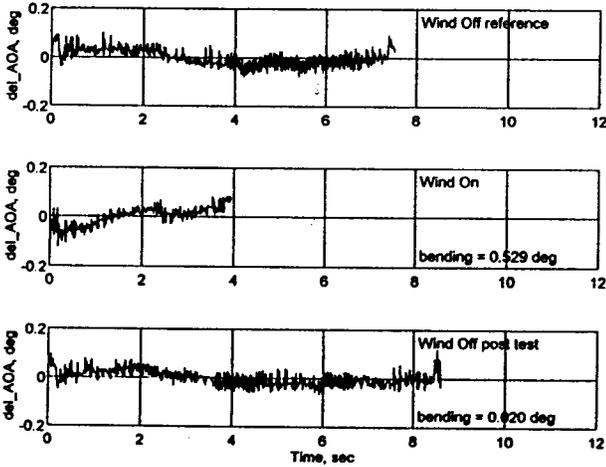


Fig. 6. Change in AOA from the mean for wind off and wind on (Mach 6) model injections at 50° AOA.

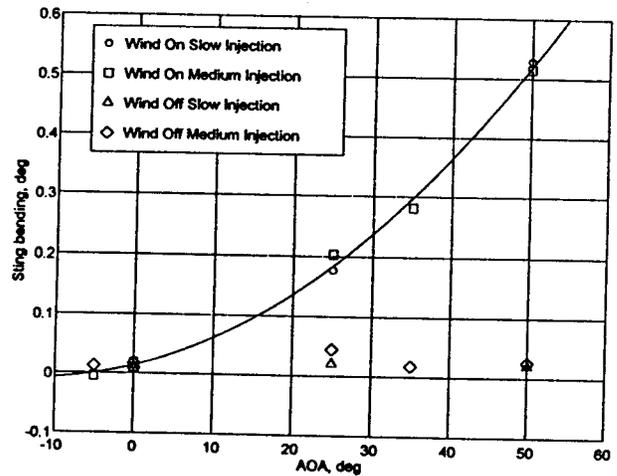


Fig. 7. Sting bending at Mach 6 as a function of AOA. Post run wind off data is plotted for reference.

3.5 14- by 22-Foot Subsonic Tunnel

The NASA Langley 14- by 22-Foot Subsonic Tunnel is used for low-speed testing of powered and unpowered models of various fixed- and rotary-wing civil and military aircraft. The tunnel can reach a maximum speed of 338 ft/sec and has a test turntable was tested. Since the angle of rotation was in the horizontal plane, an inertial measurement device could not be used to determine the angle of attack. To obtain high quality angle of attack data an Optotrak® measurement system developed by Northern Digital of Canada, owned and operated by Boeing¹⁴, was used instead of the turntable encoder for the primary measurement of angle of attack. The Optotrak® measurement system is essentially a 2 camera, 2-view photogrammetric system employing a pair of crossed linear arrays instead of area arrays. Several LED's were placed in the

model body for viewing by the Optotrak® system. The video angle system viewed the white rounded edge of the body contrasted against the black turntable since back illumination was not feasible. Additional lamps were used to illuminate the model for the video system. During wind on conditions the body could shift slightly revealing a normally hidden surface which could alter the edge location in some cases and contribute to error in the video angle measurement. Both systems viewed the model through windows in the top of the test section. The wind off calibration of the Optotrak® and video systems were verified with a portable 5 inch indexing table located in the test section which has an accuracy better than one arcsecond (0.0003°). The video system viewed a black/white edge mounted on the indexing table, while the Optotrak® system viewed a mounted bar containing LED's.

The data from the calibration is depicted in fig. 8 where the Optotrak® residuals are plotted as circles and two separate runs of the video system are plotted as squares and triangles. The top plot shows both systems on the same plot while the lower plot shows the Optotrak® residuals only. The maximum residual for the Optotrak® data is 0.013° whereas the largest video residual is 0.033°. Note that both systems show a cyclical pattern and that the repeatability and residual errors are larger for the video system in the test section compared to that obtained in the laboratory. For the following tests both systems viewed the model and the Optotrak®, as the primary angle of attack system, was used for in place initial calibration of the video system.

Wind off pitch sweeps showing the residuals for the encoder and video system compared to the Optotrak® are plotted in fig. 9 where the video residuals are represented with x's and the encoder residuals are represented with squares. The 0.13° backlash of the encoder was subtracted for the sweep from 30° back to -10°. The differences for the video data were generally within 0.02° except for the 30° reading, whereas the encoder data has much larger residuals.

Comparisons of the video, encoder, and Optotrak® angle data are presented in fig. 10 for 7 runs at Mach 0.2. Three sets of differences are plotted with the differences between the video and Optotrak® plotted as circles, the differences between the Optotrak® and encoder plotted as squares, and the differences between the video and encoder plotted as triangles. Such comparisons point out, for example, problems encountered with the encoder for some data points. Before this data set the Optotrak® was re-zeroed without re-zeroing the video system which accounts for the offset of the video data. If the slope and offset are removed from the video data the range of the residuals is $\pm 0.03^\circ$ as shown in fig. 11 for the 7 Mach 0.2 runs. The difference in slope between the video and Optotrak® is currently attributed to wind on shifts of the body that revealed a normally hidden edge that the edge detector locked onto instead of the true edge. For future comparison tests it is expected that the video system will use the same LED targets as Optotrak® and do target centroiding instead of edge detection.

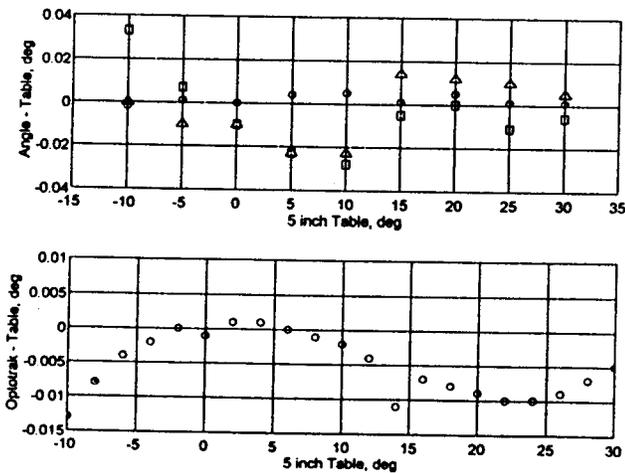


Fig. 8. Wind off calibration with a portable indexing table located in the test section.

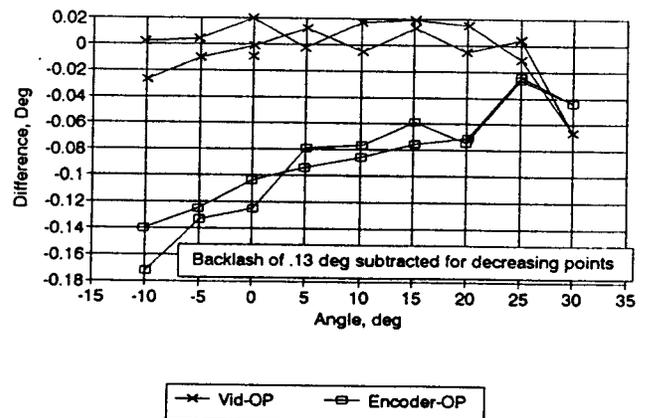


Fig. 9. Wind off pitch sweeps comparing the video system and encoder to the Optotrak® system.

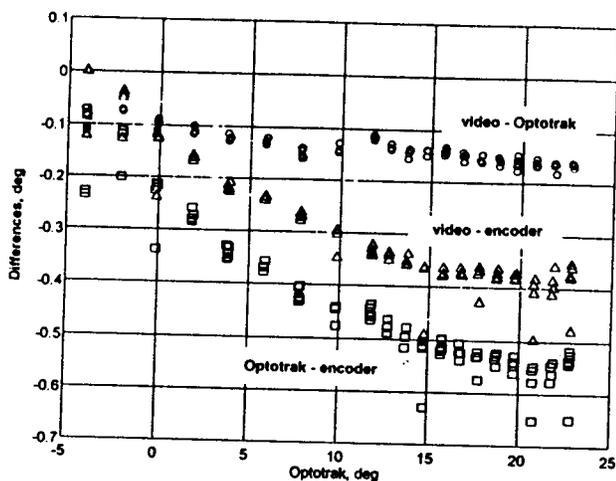


Fig. 10. Comparisons between three angle measurements for 7 runs at Mach 0.2.

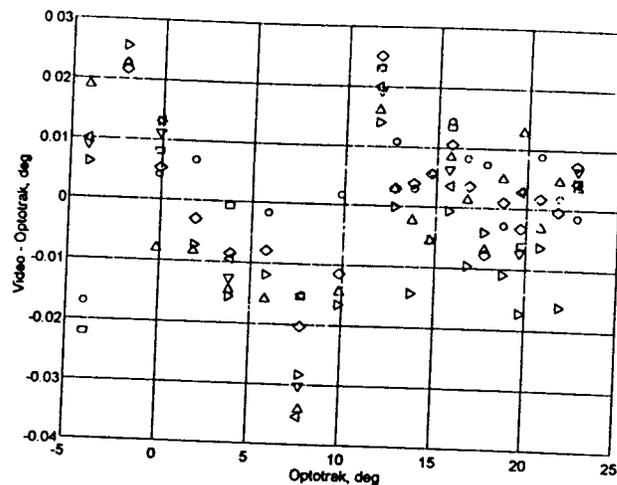


Fig. 11. Video residuals from figure 10 after removing slope and offset.

4. AERONAUTICS DESIGN / TEST ENVIRONMENT PROGRAM

There is currently a need to improve the productivity of existing wind tunnels, improve the quality and extent of knowledge extracted and radically change the role of wind tunnels in the aircraft development process. The emphasis of the Aeronautics Design / Test Environment (ADTE) program is on addressing the role of the wind tunnel in the overall aircraft development process to 1) reduce the cycle time of the wind tunnel process, 2) extract more pertinent and accurate data for the wind tunnel environment and 3) change the role of the wind tunnel from passive to active in the design process to significantly reduce the aircraft design time. The main objectives of the program, which is managed from NASA Ames Research Center, are 1) develop increased confidence in wind tunnel to flight extrapolation capabilities, 2) reduce costs and time associated with the testing process, 3) increase the quality and quantity of data obtained during testing, 4) develop systems to efficiently convert data to knowledge and direct the design process, and 5) improve the ability to rapidly validate designs. A subelement of the ADTE program is the unification of production instrumentation systems to allow the capture of as much data as possible at a given test condition. This would eliminate the need to run multiple tests with different instrumentation systems, would facilitate the combining of multi-disciplines eliminating multiple test runs, and provide real time data containing a greater impact on the design process. Unification would include development of common software for cameras, common containment vessels, etc. The production instrumentation systems to be unified include pressure sensitive paint (PSP), model position and deformation, Doppler global velocimetry (DGV), and phased microphone array technology (PMAT). NASA Langley, the lead for model position and deformation, is currently collaborating with NASA Ames in the unification effort. A major component of this effort is the unification of model deformation with PSP and temperature sensitive paints (TSP).

4.1. Unification of model deformation with PSP and TSP measurements under ADTE program

Recently, temperature-sensitive paints (TSP) and pressure-sensitive paints (PSP) have been developed for temperature and pressure measurements on model surfaces in wind tunnels. These techniques utilize thermal and oxygen quenching mechanisms of luminescence to determine temperature and pressure. Compared with conventional sensors mounted at discrete locations such as thermocouples and pressure taps, the TSP and PSP techniques provide simple, inexpensive, full-field measurements of temperature and pressure with much higher spatial resolution. Therefore, these techniques have attracted considerable attention in the aerospace community^{17, 18}.

Since TSP and PSP luminescence images are obtained using a CCD camera, the TSP, PSP, and model deformation

techniques have similar photogrammetric requirements. Quantitative temperature and pressure fields on a three-dimensional model in object space are reconstructed from two-dimensional images^{19, 20}. Hence, one has to determine the exterior and interior orientation parameters in the collinearity equations that relate the coordinates in object space to those on the image plane. In PSP and TSP measurements in wind tunnels, some targets are placed on a model surface for image registration to correct the effects of non-uniformity of illumination, paint thickness and luminophore concentration. It is realized that these targets can also be used for model deformation measurements. Efforts are underway to develop an imaging system and software that can unify model deformation, PSP and TSP measurements in wind tunnels. This unified system will significantly enhance the efficiency of wind tunnel tests and extend the capability of these imaging-based techniques.

4.2 Improved system for model deformation

In order to meet the goals of the ADTE program, careful attention must be paid to the implementation details of a video-based model deformation system. A production version of the system must be as robust as possible, while maximizing integration with other instrumentation systems and minimizing its impact on the wind tunnel testing process. In addition, such a system must be highly automated and tightly coupled with the data-storage and processing facilities of the wind tunnel. One of the goals of the ADTE program is that preliminary results from advanced optical measurement systems should be readily available to the researchers and test engineers in an electronic form within several minutes of data acquisition. These requirements form a basis for continued evolution of the model-deformation system as experience is gained in production settings.

The continuing rapid improvements in computer and video hardware provide many opportunities for improving the robustness and performance of the single-camera videometric system without sacrificing the low cost and simplicity of the system. A next-generation model deformation system is currently under development, and will exploit some of these advances while incorporating lessons learned from using the model deformation system in actual wind tunnel testing as described earlier. One of the important recent developments is the shift to high-performance 32-bit peripheral buses, such as PCI, in personal computers. This has led to the development of inexpensive video-acquisition boards for PCs which greatly improve system throughput without resorting to the use of on-board memory or signal processors. The increased processing speed can be used in several ways. By using more fields of video data per wind-tunnel data point (for example, 30 or 60 fields in a second instead of the current 15), the new system will be more immune to anomalies related to model dynamics by providing better statistics in the measured angular data. Increased system speed also makes practical the use of higher-resolution video cameras, which can help with operational details, such as the required size of targets on the model. Most importantly, increased speed opens the door to more sophisticated solutions to the complicated problems of target-detection and sorting, while maintaining the goal of near-real-time performance. By using a combination of active target tracking (instead of passive searching in each field) and pattern recognition, the robustness of the model deformation system will be greatly improved by reducing its sensitivity to extraneous bright areas in the image. This will allow highly automated operation, and will improve the flexibility of the targeting and lighting options for the system. This is highly desirable in sensitive environments such as NTF, and will increase the probability of successful integration with other optical measurements. With these improvements, the system will be able to function more like a traditional instrument, returning current data on demand for wing twist or model attitude.

The new system will also use an upgraded version of the model deformation software that requires less user intervention. This will permit unattended operation for extended periods, with model deformation results delivered automatically to the wind-tunnel data system. As part of the ADTE program, the new system will interface with the advanced DARWIN²¹ and ServIO systems at the Ames 12-foot wind tunnel. These systems allow for real-time sharing of data between cooperating instrumentation systems, storage of data using standardized file formats, and data searching based on selected metadata parameters.

5. CONCLUDING REMARKS

Given a high contrast edge or high contrast wing targets it is possible to make automated pitch angle or model deformation measurements with relatively inexpensive and straight forward videometric image processing systems. Tests have been conducted at several wind tunnels at NASA Langley and at NASA Ames which demonstrate the value of the measurement systems, especially for the determination of model deformation. However, more study is needed before the single camera, single view videometric measurement technique described here is suitable for routine operations as the primary angle of attack measurement system at a production wind tunnel. However, the technique has been used successfully for model injection and sting bending measurements at a hypersonic facility where it would be very difficult to make the same measurements with inertial or other optical techniques. In addition, videometric model deformation measurements have

proved valuable to calibrate/validate finite element methods used to predict the change in wing twist and bending due to aerodynamic loading for several advanced subsonic technology wind tunnel models as well as to provide aeroelastic data for several research models. Advances made under the Aeronautics Design / Test Environment program are expected to significantly enhance the efficiency of wind tunnel testing and extend the capability of imaging-based techniques such as pressure and temperature sensitive paint.

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