Model Deformation Measurements at NASA Langley Research Center

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1. SUMMARY

Only recently have large amounts of model deformation data been acquired in NASA wind tunnels. This acquisition of model deformation data was made possible by the development of an automated video photogrammetric system to measure the changes in wing twist and bending under aerodynamic load. The measurement technique is based upon a single view photogrammetric determination of two dimensional coordinates of wing targets with a fixed third dimensional coordinate, namely the spanwise location. A major consideration in the development of the measurement system was that use of the technique must not appreciably reduce wind tunnel productivity. The measurement technique has been used successfully for a number of tests at four large production wind tunnels at NASA and a dedicated system is nearing completion for a fifth facility. These facilities are the National Transonic Facility, the Transonic Dynamics Tunnel, and the Unitary Plan Wind Tunnel at NASA Langley, and the 12-FT Pressure Tunnel at NASA Ames. A dedicated system for the Langley 16-Foot Transonic Tunnel is scheduled to be used for the first time for a test in September. The advantages, limitations, and strategy of the technique as currently used in NASA wind tunnels are presented. Model deformation data are presented which illustrate the value of these measurements. Plans for further enhancements to the technique are presented.

2. INTRODUCTION

Model deformation may be defined as the change in shape of a wind tunnel model (particularly the wings and control surfaces) under aerodynamic load. 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[1].

The accurate prediction, as well as the measurement, of model static aeroelastic deformations is becoming increasingly important, especially for transonic transports. It is essential to accurately predict deformations in the wind tunnel in order to duplicate the desired CFD configuration. Deformations must often be taken into account when comparing CFD predictions to experimental measurements at off-design conditions. Increased reliance is being placed on high Reynolds number testing for configuration development and CFD validation, making accurate predictions of static aeroelastic deformations very important, since deformations increase significantly at the higher dynamic pressures associated with high Reynolds number testing. Computational methods such as the finite element method (FEM) need to be calibrated and validated with wind tunnel model deformation measurements in order to ensure accurate predictions[2].

The two fundamental techniques used to measure model deformation are photogrammetry and projection moiré interferometry (PMI). 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 development of video photogrammetric and PMI techniques for model deformation. However, turnkey 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. An exception to this is the commercially available photogrammetric system made by Northern Digital known as Optotrak, which has been successfully used by Boeing for both wind tunnel and flight aeroelastic and angle of attack measurements[3, 4].

The history of the development of a model deformation measurement capability for the National Transonic Facility is presented in reference 5 which includes the rationale for the 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 5. A description of the automation of the video photogrammetric model deformation technique, experimental procedure and data reduction, description of software, and targeting considerations are given in reference 6. Examples of variations of the model deformation technique used for the measurement of angle of attack, sting bending, and the effect of varying model injection rates are presented in reference 7. A brief description of the Aeronautics Design / Test Environment Program, a NASA program to improve the productivity of and amount of knowledge extracted from existing wind tunnels, is also presented in reference 7. Reference 7 also discusses the unification of several wind tunnel instrumentation techniques, including model attitude and deformation, pressure sensitive paint (PSP), Doppler global velocimetry (DGV), and phased microphone array technology (PMAT).

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. Angular measurements such as model pitch are common in wind tunnel testing. Thus, with wind-off, the measurement of the change in pitch angle at various stations along the wing can be used for in situ calibration. Deflection measurements, however, are not a common part of wind tunnel testing, making in situ calibrations more difficult. For these reasons the emphases in the development of a model deformation capability has been on the accurate, repeatable, and routine measurement of the change in wing twist due to aerodynamic load. Less emphasis has been placed on the measurement of wing bending.

2.1 Additional Model Deformation Developments

There have been several in-flight measurements of model deformation besides the Optotrak measurements made by Boeing mentioned above. An electro-optical deflection measurement system was developed by Grumman[8] and used at NASA Dryden for flight tests[9]. The Grumman system uses synchronized LED's is a manner similar to the Optotrak system.

Rotating blade deformation measurements have been made and additional studies are planned. A nonintrusive optical method has been used to measure propeller blade deflections at NASA Lewis[10]. The basic system consisted of a photodiode and a single laser used to illuminate the leading and trailing edges of the blade. The photodiode output was recorded on tape for later reduction. The Army is currently investigating the deformation measurement of helicopter rotor blades on a test stand at NASA Ames[11]. A camera will be located on the rotating hub to view a single blade. The single camera, single view photogrammetric technique is currently under consideration for data reduction.

Model deformation measurements have been made with stereo observations with the RADAC[12] and ROHR[13] measurement systems at ONERA in France. The RADAC system uses special cameras that contain crossed linear arrays. The ROHR system employs two conventional cameras. Optical fibers and quadrant light detectors in addition to a polarization torsionometer have also been used in the past at ONERA for model attitude and deformation measurements[14, 15].

Projection moiré intererometry (PMI) has been investigated by DLR in Germany for the measurement of hinge moments and model deformation[16]. (PMI is also being investigated at NASA Langley. See section 6 below.) PMI was chosen by DLR over techniques such as coded light, holographic interferometry, speckle interferometry, and different moiré techniques because PMI is easy to set up and use and can be easily adapted to measure the deformation of a wide range of model geometries. Flap bending angles due to aerodynamic load have been measured by DLR at the transonic wind tunnel (TWG) up to Mach 1.15. An average deviation of ±0.01° from strain gauge measurements was achieved. Wing twist and bending for a transport model at the Deutsch-Niederlandischer-Windkanal (DNW) have been measured with a standard deviation of 0.1 mm and 0.03° respectively. A special implementation of the system for routine wing twist and bending measurements has recently been commisioned[17] under cryogenic conditions and worked satisfactorily at the European Transonic WindTunnel (ETW). Further improvements to the system for ETW are currently underway.

Further discussions of model deformation measurement developments and applications can be found in reference 18, which summarizes a workshop on AoA and model deformation held at NASA Langley last year. The workshop was held in conjunction with the International Strain Gauge Balance Symposium. The thrust of the workshop was to assess the state of the art in AoA and model deformation measurement techniques and discuss future developments.

3. EXPERIMENTAL PROCEDURE

The optical technique used to determine the change in wing twist and bending due to aerodynamic loading is based upon the recording and analysis of digitized video images with the single camera, single view photogrammetric approach. 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 PC which records a predetermined number of video fields into the frame grabber memory. The adjustable field integration time of the charge-coupled device (CCD) video camera is set to 1/250 sec or less in order to reduce the effects of dynamics on image recording. Fixed focal length lenses have been used at the TDT, UPWT, and 12-Ft. A 10 to 100 mm focal length remotely controlled zoom lens is currently used for imaging at the NTF and UPWT. Considerations when calibrating zoom lenses for wind tunnel use are discussed in reference 19.

Image plane coordinates of wing targets are automatically measured and used to determine the X, Z coordinates (X is in the flow direction, Y points out the right wing, and Z is up) as outlined in reference 6. Reference 6 more fully describes the relations for the single camera, single view photogrammetric approach and the automated image processing software. The slope angle and offset in planes parallel to the X, Z plane are determined at each spanwise target location. Angular corrections are made based on wind-off polars. The change in wing twist at each span location is then computed as the difference between the wind-on wing angle (zeroed at 0° angle of attack with the wind-off polars) and the body angle of attack.

3.1 Calibration

The initial pre-test calibration procedure 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[20]. The point of symmetry for distortion is determined in situ from the point of image symmetry of the zoom lens[19] or laboratory laser illumination technique. 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 if a zoom lens is used. In such cases for a fixed focal length lens, a previous value (or center of image plane if previous value is not available) is used for the principal point. 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 that is aligned to the coordinate system of the tunnel. A target plate consists of a flat black aluminum or

hard foam plate with an array of flat white targets or retroreflective targets with locations measured by a 3-D coordinate measurement machine. For sting mounted models, 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. This technique for determining the principal distance is described in reference 7.

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 measured change in pitch angles at each semispan location on the wing track with the onboard accelerometer angle. 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.

3.2 Additional Wind Tunnel Considerations

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 all the facilities except the NTF. A light source placed near the camera will yield a very high contrast image when the retroreflective tape targets are used. It was recently demonstrated at a test at the Ames 12-Ft Tunnel that it is possible to use PSP reference targets and existing test section lighting, in place of the usual high contrast wing targets, with the next generation video photogrammetric system currently under development. Tests at Ames with UV illumination and PSP targets, while encouraging, were not entirely successful.

Retroreflective tape targets have not yet been used at the NTF due to difficulties in locating a light source sufficiently close to the camera and concerns about the aerodynamic effects due to the thickness of the tape. 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 can be used for correction of data along the wing span. If model dynamics are high, causing the accelerometer angle measurement to be suspect, the body angle results can be used as an alternate source for the angle of attack measurement itself. The subtraction of the body angle data from the outboard wing angles has generally been found to reduce data scatter when comparing repeat runs taken throughout a test.

Currently the final data reduction, requiring just a few minutes, using wind-off polars for correction does not occur until the end of a series of runs. The data reduction procedure is written in MATLAB and executed in the MATLAB environment. In the future it is expected that raw angles and Z values for each semispan location will be transferred to the facility data acquisition system for final reductions in order to reduce operator requirements for the model deformation system.

4. WIND TUNNEL EXAMPLES

Aeroelastic deformation measurements have been made for a number of tests at four large production wind tunnels at NASA and a dedicated system is nearing completion for a fifth facility. These facilities are the National Transonic Facility (NTF), the Transonic Dynamics Tunnel (TDT), and the Unitary Plan Wind Tunnel (UPWT) at NASA Langley, and the 12-FT Pressure Tunnel at NASA Ames. The first scheduled test for the dedicated system for the Langley 16-Foot Transonic Tunnel is in September.

The location of the data-recording camera varies with the tunnel due to window location constraints, competition with other instrumentation for viewing ports, and ease of mounting. The experimental camera locations at the various NASA facilities are depicted in figure 1. Usually only one wing and the body are viewed in order to increase resolution. However, the capability exists at the NTF to view both wings simultaneously. Measurements on both wings have been made during only one test at the NTF in order to compare the right and left wing deformations since there were differences in the pressure tube routings between the two wings. Sting mounted horizontal models are viewed at the NTF, UPWT, and 16-Ft. A sting mounted vertical model was viewed for one test at the UPWT in order to allow for PSP measurements to be made in conjunction with the deformation measurements, but translations while pitching the model in the

horizontal plane make such arrangements more difficult to properly interpret displacements. Wall mounted semi-span models are viewed at the TDT. Floor mounted semispan and Bipod supported full models are viewed at 12-Ft.

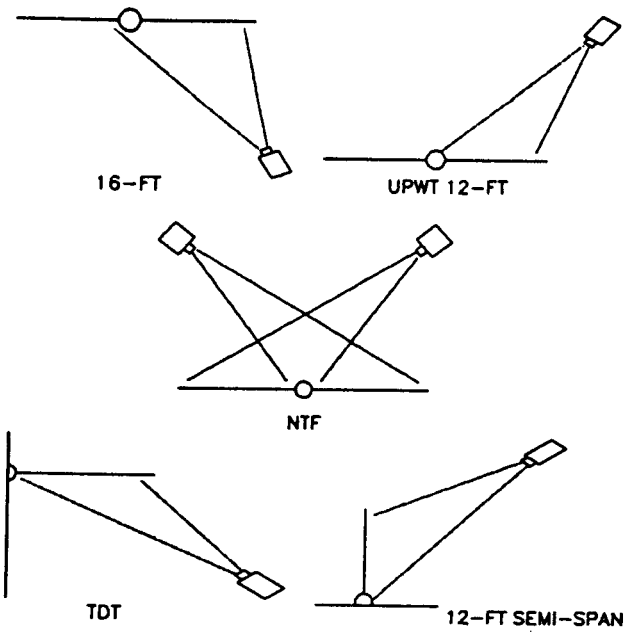

Figure 1. Sketch of camera locations at NASA facilities.

4.1 National Transonic Facility

The National Transonic Facility (NTF) is a fan-driven, closed circuit, continuous-flow pressurized wind tunnel[21]. 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° 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.

Aeroelastic deformation measurements have been made at the NTF for both High Speed Research (HSR) and Advanced Subsonic Technology (AST) models. As an example of the demand for deformation measurements, the last four tests before the recently scheduled tunnel enhancement shutdown at the NTF all had a requirement for deformation measurements. High demand for such measurements is expected to continue when the NTF returns to full operations after the scheduled shutdown.

Examples are presented below of wing twist data from the NTF at low Reynolds number. A model of a generic transport wing/body configuration was tested with and without an outboard aileron deflected. Aerodynamically induced changes in model wing twist were measured at 95% semispan. Test results are presented at both subsonic and transonic Mach numbers below. Positive aileron deflection, $\delta_{a,OB}$, is defined as positive for the trailing edge down. The changes in wing twist due to aerodynamic load, θ, are plotted versus lift coefficient, C_L, and angle of attack, α. Figures 2, 3, and 4 show Mach 0.5, 0.82, and 0.85 wing twist data respectively. As expected, positive deflections increased the lift outboard and, consequently, increased the static aeroelastic deformations at the measured 95% semispan location.

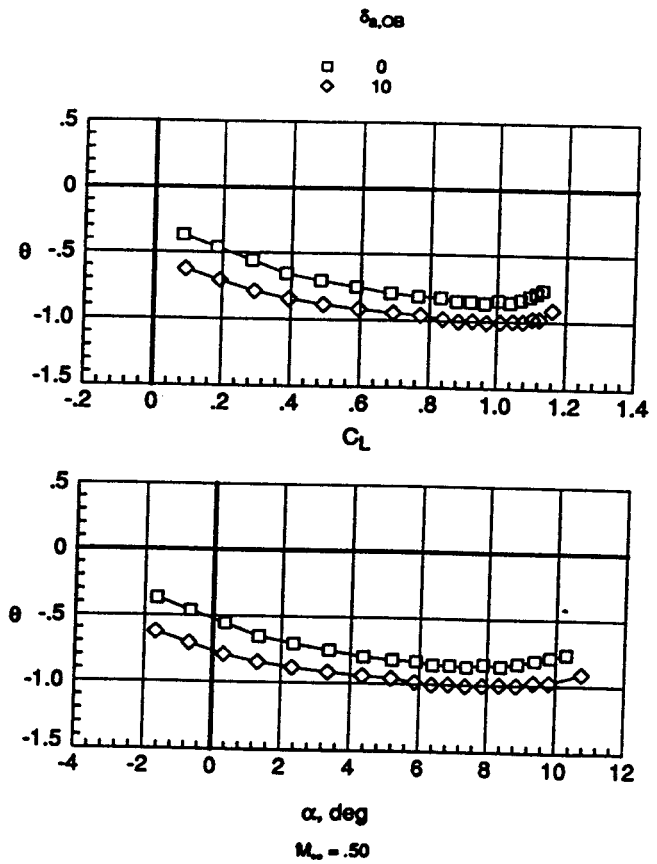

Figure 2. Effect of outboard aileron deflection on the model aeroelastic deformation at Mach 0.5 at the NTF.

4.2 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-

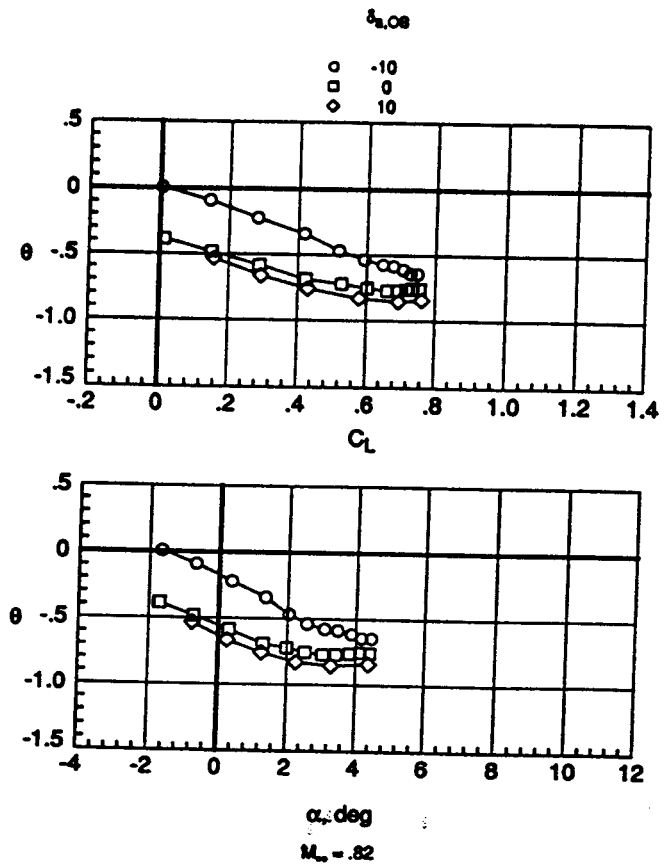

Figure 3. Effect of outboard aileron deflection on the model aeroelastic deformation at Mach 0.82 at the NTF.

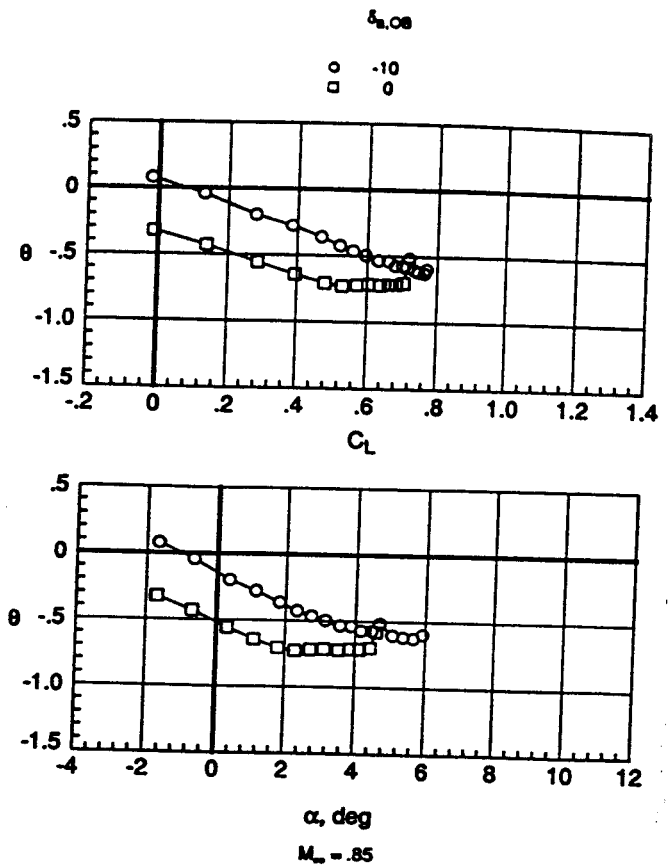

Figure 4. Effect of outboard aileron deflection on the model aeroelastic deformation at Mach 0.85 at the NTF.

wing flight vehicles and launch vehicles[21]. Semispan sidewall-mounted vehicles and full-span sting-mounted or cable-mounted models can be used. In addition, a rotorcraft testbed 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 laboratory wing loading tests have been conducted with the automated system with a worst case agreement of 0.3 mm compared with dial gauges.

Measurements have also been made on the DARPA/Wright Labs/Northrop Grumman Smart Wing that had variable twist and adaptive control surfaces to provide continuous wing contour and variable camber[22]. Tests were first conducted on a conventional wing model without smart structures for comparison to the Smart Wing and to validate the model deformation system. The system was used to determine the trailing edge deflection angles of the Smart Wing, which were embedded with shape memory alloy (SMA). The system was also used to measure model wing twist when the SMA torque tubes were activated. The system provided near real time model control surface deflections and twist. Additional measurements are planned for the Smart Wing in January 1998, which is the first scheduled test when TDT resumes operations after a lengthy maintenance and enhancement shutdown.

The measurement system at the TDT has also been adapted for displacement measurements during a test of a piezoelectric wafer actuator to alter the upper surface geometry of a subscale airfoil to enhance performance. Results showed that the piezoelectric actuator can be used to alter the camber of a small airfoil under aerodynamic load[23, 24]. 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 at 15 locations along the edge of the wafer. Deflection measurements at various angles of attack 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.

4.3 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 sections[21]. 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 x 10^6 to 11 x 10^6, depending on Mach number. Types of tests include force and moment, pressure distribution, jet effects, dynamic stability, and heat transfer. The model deformation system at the UPWT has sufficient automation that facility personnel now fully operate the system, including calibration and validation, for 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.

The model deformation measurement system at the UPWT has also been used in a special test to assess the "modern design of experiments" approach. The advantages of the modern design of experiments approach to wind tunnel testing were compared with the conventional pitch-polar "classical" design to identify the relative costs and benefits of each approach in actual wind tunnel test conditions. "Modern" designs seek to minimize resources by simultaneously changing independent variables to assess their joint impact on response variables. Because "classical" designs change only one variable at a time, they can be more costly than modern designs. The modern design can also help in data analysis in discovering effects that might be overlooked in a classical design.

The comparison test between modern and classical designs at the UPWT consisted of the measurement of aerodynamically induced wing twist at five semispan locations on the wing of a slender wing/body/tail configuration over selected ranges of Mach number, Reynolds number, and angle of attack. For this test, a savings in wind-on minutes of approximately 60% was achieved when Modern Design methods were used in place of the conventional pitch-polar (classical) method. The resource comparison is shown in figure 5 that compares the number of data points and wind-on minutes for the modern and classical approaches.

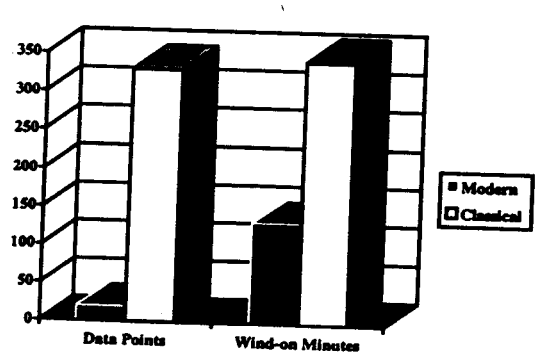

Figure 5. Resource comparison of classical and modern experimental designs.

Figure 6 plots the change in wing twist due to aerodynamic load versus angle of attack for one of the semispan locations. The classical data are plotted as solid rectangles with the corresponding 95% prediction interval plotted as the jagged line. The 95% prediction interval results from the modern design are plotted as the smoothly varying lines that are noted to agree very well with the classical data. An important point to note regarding this data is that the classical data consists of

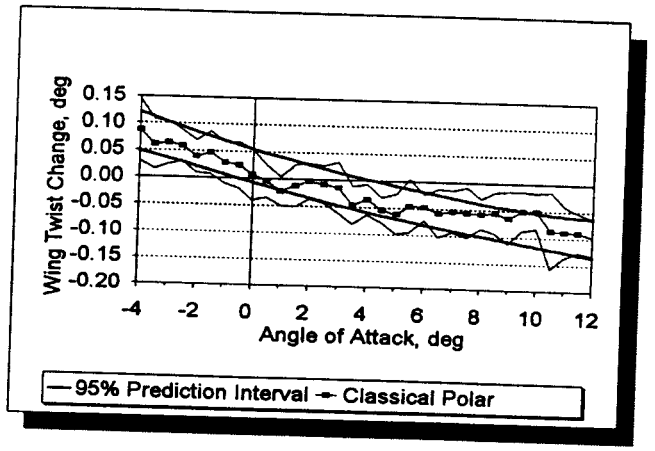

Figure 6. Comparison of classical data and prediction intervals to those found with the modern approach.

32 data points, while for the modern design results, **not a single data point was taken at the particular Mach number and semispan location where the classical data were taken.** The curve fit that represents the modern results for this plot was obtained from the wing twist response surface generated as part of the modern design analysis. The results of the comparison test were considered very encouraging and have led to additional tests of the modern method using more common aerodynamic variables at other NASA facilities[25].

4.4 Ames 12-Ft Pressure Tunnel

The restored 12-Foot Pressure Tunnel at NASA Ames is a closed-return, variable-density tunnel with a continuously variable Mach number from 0.05 to 0.60. Maximum Reynolds number is 12 million per foot. The twelve-foot diameter, 28.5-foot long test section has 4-foot wide flats on the ceiling, floor and sidewalls. The entire test section rotates to permit installation or removal of fully assembled models, which reduces model access time by 2/3 from the original tunnel. The 12-Foot tunnel is the only large scale, pressurized, very low turbulence, subsonic wind tunnel in the United States. It provides unique capabilities in high Reynolds number testing for the development of high-lift systems for commercial transport and military aircraft and high angle of attack testing of maneuvering aircraft.

A variety of model support systems are available, including bipod, semispan floor mounting, rear sting, and high angle of attack support. To date, aeroelastic model deformation measurements have been made for two tests, a full model supported on the bipod and a semispan model floor mounted vertically. For the bipod supported model the deformation system viewed retroreflective targets placed at various

semispan locations along the right wing and body. The CCD camera was installed for protection in a pressure vessel with window. An incandescent lamp was placed near the camera in the same viewport in order to illuminate the retroreflective targets. Part of the wing had to be painted flat black to eliminate specular reflections where the surface normal bisected the camera and light source locations.

The second model deformation test at 12-Foot was conducted in conjunction with pressure sensitive paint (PSP) measurements for the first time in a joint Ames-Langley wind tunnel experiment under the Aeronautics Design / Test Environment (ADTE) program. The emphasis of the ADTE program, which is managed from NASA Ames Research Center, is 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. 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).

The next-generation model deformation system was used for the first time in the semispan test to make aeroelastic wing twist and bending measurements on a 7.25% MD-11 semispan model using PSP reference targets. For this high lift PSP and model deformation test, Mach number ranged from 0.23 to 0.3, dynamic pressure ranged from 140 to 328 psf, Reynolds number ranged from 2.9 to 6.7 million per foot, and angle-of-attack ranged from -6° to 23°. The model deformation data from this test was especially needed since finite element methods were not used to predict aeroelastics due to the complicated nature of the high lift configuration. The new deformation measurement system employed an optimization method for determination of the exterior and interior orientation parameters of a camera to simplify and reduce the time required for calibration. In addition, the new system employed a target tracking technique for robustness with non-optimum targets and background such as occurs when viewing PSP reference targets. These reference targets are placed on a model surface during PSP for image registration to correct the effects of non-uniformity of illumination, paint thickness and luminophore concentration. The increase in robustness for non-optimum target contrast is considered a major improvement over the current version, which could not locate the PSP reference targets reliably in automated mode.

4.5 16-Foot Transonic Tunnel

The Langley 16-Foot Transonic Tunnel is a single-return atmospheric wind tunnel with a slotted transonic test section and a Mach number range o 0.2 to 1.25.[21] The octagonal test section measures 15.5 ft across the flats. The tunnel is used for force, moment, pressure, flow visualization, and propulsion-airframe integration studies. Models are mounted in the test section by sting, sting-strut, or semispan support arrangements.

The dedicated model deformation system for the facility is suitable only for sting mounted models at present. The CCD camera, light source and power supply are currently mounted on a movable flat of the test section which must be compensated for with wind-off polars at the various flat angular settings. The compensation scheme for the movable flat remains to be tested. A flat mirror is used to direct the light from a 150-watt lamp around the camera and out the same window. The light output is variable from the control room. A vortex cooler requiring a pressurized air supply is used to reduce the temperature near the camera, which may reach 170° F without cooling. The model center of rotation is located near to the wing area, which enables a smaller field of view in order to increase resolution.

The first test at 16-Ft with the recently installed dedicated system is currently scheduled for September 1997. The next-generation deformation measurement system will also be used for this test for evaluation while viewing PSP reference targets that will be on the upper wing surface while the current version views retroreflective targets on the lower wing surface. The PSP and model deformation measurement systems, while still separate systems, will be installed with the intent to take PSP and deformation as close to the same time as practical.

5. NEXT-GENERATION VIDEO MODEL DEFORMATION MEASUREMENT SYSTEM

The next-generation model deformation system currently under development will exploit advances in video and computer hardware 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 the NTF, and will increase the prob-

ability 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 DARWIN[26] and ServIO systems. 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.

6. OTHER NASA LANGLEY MODEL DEFORMATION MEASUREMENT DEVELOPMENTS

Projection Moiré Interferometry (PMI), a second method for measuring wind tunnel model deformation, has been under development at NASA Langley[27]. PMI is a simple, yet powerful technique that has been used since the early 1900's for surface topology and shape characterization. Past efforts to use PMI for wind tunnel model deformation measurements revealed limitations in the technique - particularly directional ambiguity. Recent advances in electronic image acquisition and image processing have overcome these limitations, and have made PMI a viable instrument capable of measuring whole field, 3-component displacement vectors of any visible point on the model surface.

A single component PMI system consists of an illumination source, Ronchi ruling, CCD camera, and frame grabber. Using the illumination source and ruling, a series of equispaced, parallel lines are projected onto the object surface. A reference image is acquired in a non-deformed (or wind off) condition to digitally record the projected line pattern. Under load, the model will have moved, and the projected lines will appear to lie in different spatial locations. When subsequent images of the deformed state are acquired and subtracted from the reference image, moiré fringes are formed. The geometric configuration of the instrument and projected line pitch dictate the moiré fringe spacing. Using this relation and fringe counting via image processing, the displacement field can be determined. With commercial hardware and generic RS-170 video cameras, fringe sensitivities of 0.5 mm are common. Advanced image processing and fringe interpolation techniques can extend this resolution to 1/10 to 1/20 of a fringe.

In contrast to video photogrammetry, PMI requires no surface preparation or registration targets to be placed on the model. The off-line deformation analysis is done whole field, rather than by curve fitting between targets. Moiré fringes can be observed in real time providing the test engineer immediate video feedback regarding model position. If desired, this capability allows the engineer to reposition the model to account for differences between wind-off and wind-on body AoA before acquiring aerodynamic data. With the proper illumination source, both PMI and video photogrammetry can be used with other optical wind tunnel instrumentation systems simultaneously. At NASA Langley, PMI systems are being designed with high power, 800-810 nm laser diodes as the illumination source. When selectively filtered, this permits simultaneous operation with such techniques as Pressure Sensitive and Temperature Sensitive Paint (PSP and TSP), conventional laser velocimetry, and Doppler global velocimetry (DGV).

Because PMI is still under development as a wind tunnel instrument, video photogrammetry remains the predominant model deformation tool used at Langley. PMI is currently being investigated for measuring dynamic rotor blade deflection, and for unification with other instrumentation systems. Towards these goals, two proof-of-concept tests have been planned: (1) a combined PMI/DGV rotor craft test in the Langley 14- x 22- foot tunnel to investigate rotor blade / wake vortex interaction, and (2) a unified instrumentation test in the Langley Unitary Plan Wind Tunnel comprised of PMI, video photogrammetry, DGV, and PSP. Long term PMI applications include measuring deformation profiles of active feedback controlled rotor blades in simulated flight conditions.

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