Model Deformation and Optical Angle of Attack Measurement System in the NASA Ames Unitary Plan Wind Tunnel

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Both AoA and MDM measurements can be made using an optical system that relies on photogrammetry. Optical measurements are being requested by customers in wind tunnels with increasing frequency due to their non-intrusive nature and recent hardware and software advances that allow measurements to become near real time. The NASA Ames Research Center Unitary Plan Wind Tunnel is currently developing a system based on photogrammetry to measure model deformation and model angle of attack. This paper describes the new system, its development, its use on recent tests and plans to further develop the system.

Nomenclature

AoA	Angle-of-Attack
AEDC	Arnold Engineering Development Center
ARC	NASA Ames Research Center
COTS	Commercial Off-the-Shelf
FPGA	Field-Programmable Gate Array
LaRC	NASA Langley Research Center
M	Mach Number
MDM	Model Deformation Measurement
OAoA	Optical Angle of Attack
UPWT	Unitary Plan Wind Tunnel
X	Streamwise 3D Coordinate
Y	Spanwise 3D Coordinate
Z	Gravity Vector 3D Coordinate

I. Introduction: Requirements on Optical Angle of Attack and Model Deformation Measurement Systems

As aircraft performance improves and marginal gains become smaller and more difficult to resolve, new and more accurate wind-tunnel measurement techniques are required. Two particular needs expressed by

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test customers of the NASA Ames Research Center (ARC) Unitary Plan Wind Tunnel (UPWT) are: 1) accurate measurements of angle of attack when the model is in the vertical plane and; 2) measurements of model deformation under airloads. These needs can potentially be addressed by similar solutions.

A.   Angle of Attack

Knowledge of the model angle with respect to freestream velocity allows lift, drag, and side-force to be resolved into their separate components. Any uncertainty in the flow direction relative to the model creates systemic uncertainty in drag and side-force. In particular, drag must be isolated from the other forces in order to make accurate cruise performance measurements. The angle which the model makes to the flow is composed of angle-of-attack and sideslip angle. Of these, angle of attack (AoA) is more critical because lift is generally large compared to drag and side-force.

Accurate AoA measurements allow axial and normal forces to be accurately decomposed into lift and drag. It is widely accepted within the wind tunnel community that in order to resolve one drag count ($\Delta C_D = 0.0001$) AoA should be measured to an accuracy of $0.01°$.[1] Measurement of this quantity is generally divided into two tasks: 1) measure the direction of the flow relative to the wind tunnel and 2) measure the orientation of the model relative to the wind tunnel. The first, flow angle, may be known from previous studies or may be measured in situ based on pressure measurement at the walls. Flow angularity can also be ascertained by comparing measurements with the model upright and inverted. The second, model angle, can be measured with the required accuracy of $0.01°$ relative to the gravity using accelerometers, but this requires the model to be oriented "wings horizontal" such that AoA is in the vertical direction. However, when the model is oriented "wings vertical" and AoA is in the horizontal direction, accelerometers cannot be used to measure AoA, and the conventional alternative– measurement of the sting angles with corrections for deflections due to model loads– does not provide the needed accuracy of $0.01°$.

B.   Model Deformation

Wind tunnel models deform slightly under airloads, which changes their aerodynamic shape and thus their performance. For example, in the ARC UPWT the model Reynolds number at a fixed Mach number is changed by altering the tunnel operating pressure. This also changes the airloads on the model, so performance changes which are assumed to be due to Reynolds number effects may be the result of model deformation instead.

Model deformation is usually expressed as the bending and twist of the wing, as the wing is generally the most flexible part of the model and has the greatest effect on aerodynamic performance. The wing bends around its neutral axis and bending increases from root to tip. If the wing is swept back this will cause the wing to twist slightly as it bends, with the change in twist increasing toward the tip. As the wing's aerodynamic properties are very sensitive to changes in pitch angle, this local wing twist is actually the major aerodynamic effect caused by wind tunnel model deformation.

The accuracy requirement for wing twist measurements is not well specified.

II.   Current Model Deformation and Angle of Attack Measurement Capabilities

There are many ways to make both AoA and model deformation measurement (MDM) measurements. Facilities around the world are choosing to employ various techniques based on their typical test requirements and optical access to the test section. Tunnels either deploy a system developed in-house or a commercial off-the-shelf system depending on their needs and the flexibility of the system required. Systems can be either traditional or optically-based.

A.   Commercial Off-the-Shelf Systems

There are commercial off-the-shelf (COTS) options for making MDM and AoA measurements. The use of COTS systems can save time compared to developing an in-house solution. However, these systems usually have constraints built into them that do not make them flexible enough to deploy in geometrically constrained areas, nor the ability to easily integrate into the data systems already in use. Most commercial software is built for a research environment where each data point is analyzed immediately after its acquisition,

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requiring extensive user interaction. In a production level facility such as the UPWT, data points are taken successively, and the system must be quickly ready to take the next point. This process can not stop to accommodate one system's longer workflow, making user interaction a disadvantage. However, modifications or workarounds can normally be found to partially integrate them into the wind tunnel control software.

1. Vicon

Vicon is a commercially-developed photogrammetry[2] system. A Vicon system consists of two or more special-purpose cameras, a camera interface unit, and a workstation. The cameras (Fig. 1) each have a built-in ring LED lamp. The object to be measured is marked with circular retroreflective targets. This allows each camera to see the targets as high brightness objects which can be easily distinguished from the background. A field-programmable gate array (FPGA) on board each camera thresholds the image to remove all features which are not targets, then calculates the centroid of each target. Only the location of the target centroids and not the images themselves are downloaded by the cameras, allowing for faster readout speeds.

Figure 1. Vicon F40 camera showing ring LED lamp.

Cameras are placed so as to view a single measurement volume from several different locations. A calibration wand, consisting of a set of markers in a known configuration, is moved around the measurement volume so that it can be seen by all cameras. The Vicon software automatically calculates a resection for each camera which can then be used to determine the location of an arbitrary target in the measurement volume. Initially the locations calculated are in an arbitrary coordinate system. Another piece of calibration hardware, called an L-Frame, is placed at a known orientation in the measurement volume and imaged by the cameras. The L-Frame defines the coordinate system origin and orientation. Vicon is currently used at NASA Langley Research Center in the Rotor Test Cell and 14 x 22 foot Wind Tunnel.[3] While excellent for blade tracking at high speeds and in a low speed wind tunnel, making it a viable contender for AoA measurements, MDM measurements could not be made at the desired measurement resolution due to the set size of the targets using this system. The retroreflective targets are also undesirable for customers due to their height, which can trip the flow over the wing, making the wind tunnel data less reflective of the flight environment.

2. Magnetic Position Sensors

Magnetic position sensors use transducers which can sense the strength and direction of an applied magnetic field. By generating a controlled, time-varying magnetic field the sensor position and orientation relative to the field generator can be determined. Such sensors are widely used in biomedical research because the sensors themselves are small and can be placed entirely within the target object. Several manufactures were surveyed to determine if any suitable products were available. Polhemus, Inc. produces a line of magnetic position sensors which are representative of the state of the art in this field. Unfortunately magnetic position sensors have two properties which make them unsuitable for AoA measurements. Even high quality sensors are only accurate to within $0.15°$, considerably less than the required $0.01°$ accuracy. The measurement of such sensors is contaminated by the presence of ferrous metals. The wind tunnel environment, consisting of a typically steel model mounted on a steel support in a steel enclosure, degrades magnetic sensor accuracy to the point of uselessness.

3. Gyroscopes

Gyroscopes are commonly used to sense angular rotation rates. By integrating rotation rate measurements it is possible to track the orientation of the gyroscope – this principal is widely used in Inertial Measurement Systems (IMS) to measure the orientation of air and space vehicles. In principal one would use gyroscopic sensors to measure AoA by positioning the model at a known reference angle and zeroing the integration. The

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integrated gyro rate data would then provide a time history of the model angle. All gyros are subject to drift over time, and the question becomes one of whether a gyro can be found which has sufficiently low drift that the angle measurements would be sufficiently accurate over the time between re-zeroings of the integration. A gyro-based angle measurement system was developed by Rueger for the Boeing Polysonic Wind Tunnel[4] and has been demonstrated at the Arnold Engineering Development Center (AEDC)'s Tunnel 9 as well.[5] Rueger reports that the gyro sensor has a random error of <0.036°and a systematic error of <0.012°when the sting is swept in pitch-pause mode in the Polysonic Wind Tunnel. Error could not be measured as systematically in Tunnel 9, but a total 2 sigma error of 0.05°- 0.1°was reported. These error estimates suggest that a gyro-based angle sensor could potentially be used to make AoA measurements with enough fidelity in a wind tunnel, however it is not a viable option for MDM.

4. Aramis/Pontos

Aramis[6,7] is a commercial package from GOM GmbH (LLC) that measures the strain on an object using photogrammetry. An Aramis system consists of two synchronized cameras attached to a rigid mounting bar. The bar configuration allows certain assumptions to be made in the photogrammetry processing software which speed up the processing. These assumptions require additional constraints compared to a traditional photogrammetry system. For example, the intersection angle, the angle between the optical axes of the pair of cameras, should lie between 15 and 25 degrees, while in traditional photogrammetry, an intersection angle of 90 degrees in the direction perpendicular to the camera baseline provides the most accuracy. Like Vicon, calibration of the Aramis system is done by imaging a calibration object with targets of known spatial separation throughout the measurement volume. Randomly distributed circles printed, painted or glued to the model are used as photogrammetric targets.

After modification of the hardware, the software and the calibration procedure, four 5M Aramis systems working in conjunction were used in the 40x80 foot wind tunnel of the National Full-scale Aerodynamics Complex (NFAC) at NASA Ames to successfully measure the deformation of a Hypersonic Inflatable Aerodynamic Decelerator, though full surface measurements were not simultaneous.[8]

5. VMSCapture

VMSCapture by Geometric Software is a system currently employed at NASA Langley's National Transonic Facility. It has also been used in the 14 by 22 Ft Tunnel.[9] Comprised of multiple Gig-E cameras, this photogrammetry-based system uses multiple cameras to track model AoA and MDM.

The cameras' internal parameters are pre-calibrated in a lab using constant focus and zoom then recalibrated in situ while establishing the location and orientation of the cameras relative to the wind tunnel. Targets on the walls of the test section are used to determine the external scale. This system is most similar to the photogrammetry system employed at NASA Ames.

B.   In-House Solutions

In-house measurement solutions provide the most flexibility to provide the tunnel with a system that exactly meets the needs; however this option can be time consuming and expensive, depending on the level of detail required and the amount of people needed for its development. Some examples of facilities using in-house systems are The European Transonic Wind Tunnel (ETW)'s systems,[10,11] Videometric Model Deformation (VMD) systems at NASA Langley Research Center,[12] and AEDC's MDM/Optical Angle of Attack (OAoA) measurement capability that was created for use in a Pressure Sensitive Paint System.[13–16]

1. European Transonic Wind Tunnel

The European Transonic Wind tunnel (ETW) is a pressurized cryogenic high reynolds facility in Köln, Germany. The ETW uses multiple optical systems to measure model deformation.[10] The first is a full-wing optical MDM system (MDMS) using Moiré interferometry. A black and transparent parallel striped pattern known as a Ronchi ruling is projected on to the model. The image of the stripes is then focused onto an observation camera. A Moiré interference pattern is produced digitally by evaluating every second line of the image.[11] Changes in the interferogram correspond to changes in the height of the model. This technique requires extensive post-processing.

The second is a Stereo Pattern Tracking (SPT) system which measures model deformation at a series of targets placed on the leading and trailing edges of the wing(s).[10] Unlike the MDMS, the SPT system can be used on semi-span models. The targets are circular Letraset dots 10mm in diameter and 5μm thick. Two cameras, calibrated in-situ using a frame with lightbulbs of known spacing, view the targets from two different angles. The wind-on images are processed to automatically locate the targets in model coordinates and compared with previously taken reference images at each AoA. The SPT system runs at 7Hz in pitch-pause mode, collecting 21 images at each position, with a total time of 3s per point. It has a maximum limit of 40 targets. Averaged target locations show a measurement scatter of 0.5mm with a standard deviation of 0.2mm. Raw images are not typically stored on disk, though if required images can be saved but this reduces the data rate to 1Hz.

The image pattern correlation technique (IPCT) is another method used at the ETW to measure model deformation on the full surface of the wing. The location of painted speckles on the model are calculated by comparing wind on to wind off images using photogrammetry and cross-correlation, an approach developed for Particle Image Velocimetry (PIV).[10]

2. NASA Langley Research Center

One example of many systems used at NASA Langley Research center is single-camera Videometric Model Deformation (VMD) systems. VMD systems have been successfully used in the National Transonic Facility, the Transonic Dynamics Tunnel, and the UPWT at NASA Langley Research Center.[12] The VMD system consists of a single camera, looking at discrete targets on the model. Here, the need for a second camera is eliminated by assuming that the span-wise coordinates of the targets are known.

The VMD system can run in either in an automated mode in which a VMD measurement is taken each time the tunnel data system takes a measurement, or by the user initiating a data point with a keystroke. High-contrast targets consisting either of white diffuse circular targets on a black background, retroreflective tape targets, or highly polished painted targets are typically applied streamwise in a strip of six targets at a particular semispan station.

Targets are located in data images, then single-camera photogrammetry along with the assumed spanwise location Y, is used to compute the remaining object-space coordinates X,Z for each target in both wind on data images and wind-off reference images for each AoA.[12] The AoA for each row of targets is then calculated by a least-squares fit of the X and Z locations. Uncertainties of measurements made in wind tunnels with the NASA VMD systems have been reported as 0.1-0.2 mm in bending and 0.05° in twist.[12]

3. Arnold Engineering Development Center

AEDC currently uses a MDM/OAoA measurement capability that was created for use in a Pressure Sensitive Paint System.[13] Targets are applied to the model on both the wing and fuselage using a black marker and a stencil. Two scientific cameras view the model from different directions at steady state conditions. Halogen lights are used to illuminate the targets on the model. The cameras are calibrated by imaging a calibration plate containing targets of known spacing at multiple orientations to the cameras. Targets are located in the images in the same way they are in PSP through use of a search template.[14–16] The normal vectors and diameters of the targets are also calculated by analysis of the elliptical shape parameters of the targets in the images. The 3D locations of the targets are then determined by calculating the minimum distance between the two lines of sight from each camera position to the targets. A rigid-body transformation is applied to transform the resulting target positions and normal vectors to those of the test article based on the measured positions of a set of control points (such as corners) in the images.[13] The resulting 3D displacements are determined by subtracting wind off from wind on results. These measurements can then be used to correct the grids used in mapping PSP results to the model for model displacement, thus facilitating more accurate comparison of PSP data to computational fluid dynamics results. The measured deflection of an individual targets is on the order of one percent of the maximum deflection measured.

4. Office National d'Etudes et de Recherches Aérospatiales

The industrial wind tunnels at the Office National d'Etudes et de Recherches Arospatiales (ONERA) in France measure model deformation using a system that was created to correct the results of model deformation on Pressure Sensitive Paint data.[17] As PSP results are mapped back on to the model using a

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grid, it is important that the grid accurately reflect the shape of the model which has been deformed under aerodynamic loads.

The Onera system is a single camera system that does not require that one coordinate of the measurement be known or assumed, though it can be extended to multiple cameras if desired. Resection measurements are used to identify the location of the camera. Virtual images are created from another assumed camera location.

III. MDM/OAoA Systems at the NASA Ames UPWT

A. Previous Systems

During the 1980s and 1990s UPWT explored the use of three optical systems for measuring AoA. The first of these was a Laser Angle Meter developed by Boeing[18] This instrument used interferometry to measure AoA in real time to accuracies of 0.005 degrees. It consisted of an optical transmitter located outside the test section and a reflector unit mounted in the model. A laser beam from the transmitter illuminated the reflector, which include a hologram and a retro-reflector. The hologram created first-order diffracted beams as the incident and reflected beams passed through it. These beams were collected at the transmitter, and the phase shift between them was used to discern AoA. The instrument was deployed in the Boeing Transonic Wind Tunnel (BTWT) and also in the UPWT 11 x 11 TWT at Ames. A disadvantage of this system was the need to cover the detector with a window that matched the local contour of the model. In addition, the transmitter needed to be placed on a translation platform in order to track the model. Another problem was that fog in the test section would cause the system to lose track of the model, which could require shutting down the tunnel and resetting the system at a known reference condition.

The second AoA system, developed by Complere Inc., was a lateral-effect position sensor. It consisted of a laser that was mounted outside the test section and a detector mounted in the model. Light from the laser was expanded, collimated, and directed into the test section where it illuminated the detector. The detector consisted of a spatial filter, lens, flat glass plate, and a photodiode. The principle of operation was that the laser beam would be shifted laterally due to refraction as it passed through the glass plate if the beam was not normal to the plate, and the displacement would be proportional to angle of incidence. The lens in the detector focused the incident light onto the photodiode, which measured the displacement. The system was demonstrated in the UPWT 9x7 SWT and achieved accuracies of about 0.02 degrees.[19] Virtues of this system included real-time output without signal drop-out due to tunnel fog, and the potential to achieve the desired accuracy of 0.01 degrees. Drawbacks of the system included the need to fit a window in the model that matched the local contour of the model; the need to traverse the laser beam to track the model; and safety overhead due to the use of a laser.

The third optical AoA system was Optotrak, an off-the-shelf commercial system developed by Northern Digital, Inc. This is a stereo photogrammetry system that uses active infrared emitting diodes embedded in the model as targets or markers. The diodes are triggered sequentially so that at any instance only one is illuminated. This eliminates any ambiguity in matching corresponding targets between camera views. The system yields measurements of up to 256 targets in real time.

B. Current System

The current MDM and OAoA system in the NASA Ames UPWT is a system comprised of high-resolution scientific/machine vision cameras, processing software written in house, and targets and/or a speckle pattern of ink or dye that are applied to the model. Occasionally features on the model such as pressure taps can be used as targets depending on their relative size and visibility in the images. If on the rigid, non-deforming portion of the model, these features can also be used to subtract the rigid body motion of the model. The system is currently capable of making measurements with the desired accuracy range; typical results from this system provide elastic deformations smaller than 0.1 mm and changes in twist of less than 0.05°, however, the bulk of the processing is done post-test.

Corresponding targets and speckles in each image are located and then matched in one of two ways. The first, used for targets, is simply to locate the targets that have been marked on the surfaces of the models. By this method, the number of measurements is limited by the number of targets and spatial resolution is low, however data can be delivered more quickly due to the low number of points. Targets in the first image of a sequence are located by pointing and clicking on an enlarged view of each target with the computer mouse.

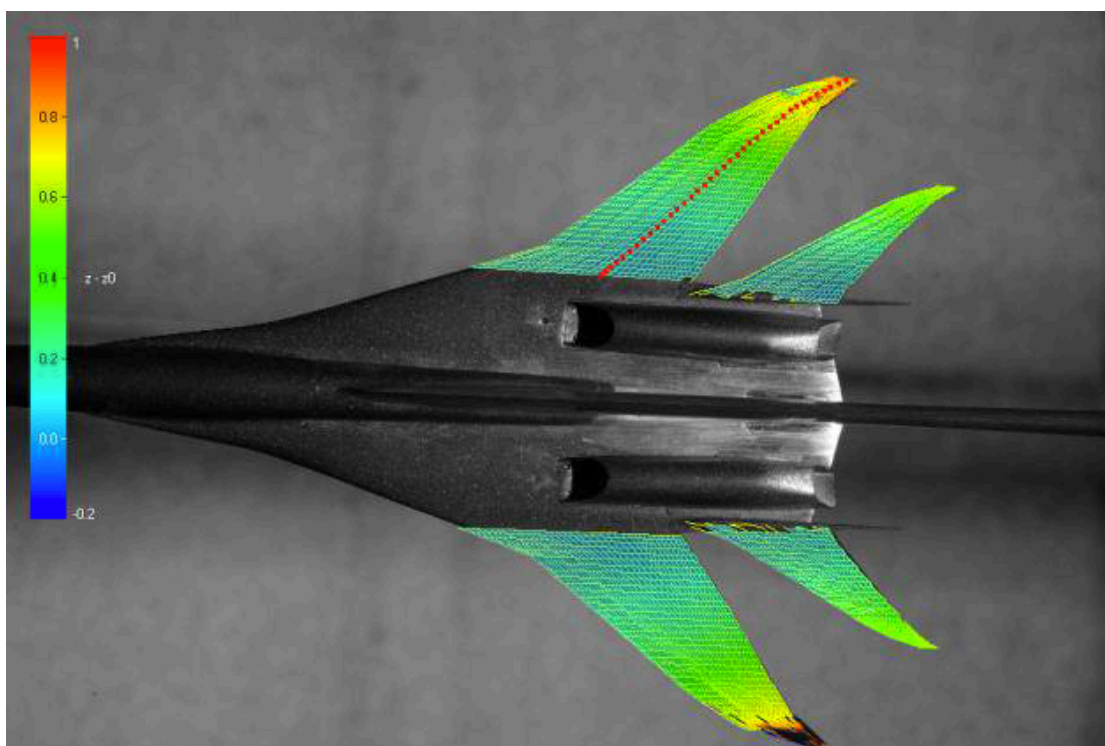American Institute of Aeronautics and Astronautics

Figure 2. Wind-on images of the Boeing Sonic Boom model with overlay of average bending from speckle measurements. Color scale extends from -0.2 mm (blue) to +0.8 mm (red).[20]

For each subsequent image in the sequence, the same targets are located automatically by searching a subset of the image near each previous target. The second method for identifying corresponding points makes use of the speckles. By this method, a surface grid for the model is projected into the wind-off image from each camera. Each node of the grid overlies a unique set of speckles and defines a point on the model where a deformation measurement is to be made. For perfect projections, each node overlies the same speckles in the images from all cameras. The displacement of each node between wind-off and wind-on images was determined by cross-correlating wind-off and wind-on image data (speckles) in a small interrogation window centered on the node. By repeating this procedure at all nodes, the wind-on image coordinates of the surface grid were defined.

Once corresponding targets or speckles are located in the images, stereo photogrammetry[2] is used to compute their object-space coordinates in both wind-on data images and wind-off reference images. The rigid-body transformation between wind-on and wind-off coordinates is computed using reference targets of known spacing on the rigid body. This transformation is then applied to all the targets, yielding their location in the body-axes. The wind-off coordinates are then subtracted from the wind on coordinates, yielding the out-of-plane bending. Twist is then calculated from these results at various stations along the wing, using linear regression of chordwise bending.

This system is an updated version of a previous photogrammetry system at the UPWT that was comprised of commercial DSLR cameras and flash lamps. The previous iteration of the system acquired image data using two LABview scripts that triggered the cameras and flash lamp simultaneously. The first script was used to acquire images and automatically downloaded,and renamed the images with run and sequence numbers. The time required to download the images, however, was excessive and severely limited the rate at which data could be acquired. The second script was was an updated version of the first and simply acquired the images and left them on the cameras' internal CF cards. Because no time was lost downloading images, more images could be acquired at each test condition. The images were retrieved from the cameras after the test.[20] Figure 2 shows an example of results from the previous system.

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1. MDM and OAoA Requirements

The photogrammetry system was designed and optimized to provide high-resolution images that captured the full range-of-motion of typical models in the Unitary Plan Wind Tunnels at NASA Ames. The target measurement resolution was to measure AoA to within 0.01°. Since this in conjunction with the need to cover a large area in which to make the measurements, drove the requirement for high-resolution cameras, static, not dynamic measurements were targeted.

The new system is modular in design, making components easily upgradeable as hardware and software improve.

2. Cameras

One improvement this new system brings is the use of scientific cameras that are more easily controlled in a repeatable manner. Imperx Bobcat 6640 cameras are both high enough resolution at 29 megapixels and take data at a high enough rate to provide steady-state data. These cameras were controlled using LABView, which many of the tunnel systems currently run on. This allowed for better integration, the labeling of images with the tunnel conditions, and automated data acquisition. The new system makes use of the current photogrammetry processing code and integrate with the LABView code to form a cohesive unit. The cameras acquired data through a LabVIEW program that was written in-house. This program interfaced with other LabVIEW programs, such as the Data System Coordinator, which allowed data to be automatically acquired. The LabVIEW program ran on a PXIe system from National Instruments to which NI-1435 frame grabbers were attached.

3. Illumination

Two different sources of illumination were with the system. Three Impact strobe lamps were used at first, however, these lamps did not trigger consistently, so the lamps were changed to using three Dynalite flash lamps.

4. Targets

Targets are created using a stencil. Appropriately sized holes, 3-6 pixels in diameter are cut in a sheet of vinyl cling wrap using a laser cutter. This creates a stencil that could be applied to an already-painted model without altering the surface. White ink (Diagraph) is then sprayed on using an airbrush.

5. Calibration

After cameras were positioned, pointed, and focused, they were calibrated in two steps. In the first step, a flat plate with a rectangular array of targets was held in the field of views of both cameras, and images were acquired with the plate at different orientations. These images allowed the internal orientations of the cameras (principal point and image scale factors) to be computed. In the second step, magnetic, retro-reflective targets were placed on the walls of the test section and their object-space coordinates were precisely measured using a commercial photogrammetry system (V-STARS). The external orientations of the cameras (positions and point angles) were computed from the image-plane and object-space coordinates of these targets.

Figure 3. Imperx Bobcat 6640

IV. Test Description

The new system was recently exercised during two wind tunnel tests in two different test sections of the NASA Ames UPWT.

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A. NASA Unitary Plan Wind Tunnel

The Unitary Plan Wind Tunnel at NASA Ames is comprised of two separate active test sections. The 11- by 11- ft. Transonic Wind Tunnel (TWT) has a square test section with slotted walls and runs from Mach 0.2 to 1.45. The test section is contained within a cylindrical plenum that is part of the pressure vessel. There is a 3 x 5 array of windows in each sidewall, where each window is 41 inches long and 8 inches high. This results in an overall viewable area of about ten by five feet. There are also three windows in both the ceiling and floor. Recently, additional small round porthole windows were added to the test section in numerous locations where optical access was lacking. Cameras and lamps are typically installed inside the plenum, and cooling air is often required when operating at low pressures.

The 9- by 7- ft. Supersonic Wind Tunnel (SWT) has a rectangular test section with solid walls and operates a between Mach 1.55 and 2.55. In each side wall there are two 28-inch diameter circular windows, each of which is eccentrically mounted in a five foot diameter turntable. These windows were designed for use with a schlieren system. Because the windows are eccentric, rotating the turntable displaces the centers of the windows making different parts of the flow available for schlieren imaging. The 9- by 7- ft. SWT also has two 22-inch x 11 inch windows in the ceiling located 7 inches from the tunnel centerline. There are no windows in the floor because of the sliding nozzle block which changes the freestream Mach number. The asymmetric nozzle creates flow curvature in the vertical plane, resulting in models being tested in the wings vertical postition, with AoA calculated from encoders/resolvers in the knuckle sleeve system that positions the model. The walls and windows are part of the pressure vessel; thus, unlike in the 11- by 11- ft. TWT, cameras and lamps can be mounted in an easily accessible, ambient environment.

B. NASA/Boeing Subsonic Ultra Green Aircraft Research Truss-Braced Wing

Model deformation measurements were made on the NASA/Boeing Subsonic Ultra Green Aircraft Research (SUGAR) Truss-Braced Wing (TBW) aircraft in the NASA Ames 11- by 11-ft. Transonic Wind Tunnel. The TBW aircraft has a very high aspect ratio wing supported by struts that run from approximately mid-span of each wing to the underside of the fuselage. Two different struts were used during testing: a baseline strut and an alternate strut. Measurements were made primarily on the bottom surfaces of the starboard wing and strut and later in the test on the top surface of the port side wing while the model was inverted. Two other optical measurement techniques, PSP and IR thermography, were also deployed on this test. IR themography data were acquired on the top surface of the starboard wing, and PSP data were acquired on the remainder of the model. To accommodate IR thermography, the starboard wing and strut of the model were painted with a matte black paint. Flexible-body targets were painted on the wing and strut with white toner ink to provide high contrast with the background. The targets on the wing were painted in chordwise rows consisting of seven targets each at seven spanwise locations on the wing. Three chordwise rows of three targets each were painted on the strut. After the PSP and IR paints were removed, flexible-body targets were repainted with black toner ink on the gray epoxy base coat. Black backgrounds were placed around plaster-filled screw holes on the underside of the fuselage to allow the screw holes to be used as rigid-body targets for the entirety of the test.

Normalized wing bending along the trailing edge and wing twist data from 10-image averages can be found in Figures 4 on the next page and 5 on the following page. Error bars indicate two standard deviations from the average – a result of both measurement uncertainty and unsteady model movement. Positive bending indicates bending towards the top of the model, and negative twist indicates a decrease in local angle of attack. The alternate strut was found to limit bending much more effectively than the baseline strut. Differences between similar baseline strut configurations were observed and are attributed to changes in wing preload between configuration changes as the struts were taken on and off the model. The only two baseline strut cases taken successively without altering the strut in Figures 4 on the next page and 5 on the following page were the Baseline strut, nacelle and Baseline strut cases, and their bending values are nearly identical. Twist was not found to vary significantly between the baseline and alternate struts. The twist measured on the port side wing (Baseline strut inverted) was much larger than that measured on the starboard wing. This is attributed to slight differences in geometry between the two sides of the model.

Twist was found to be a very sensitive measurement due to the narrow chord length (approx. 2-3 in). In some cases, the strut obscured targets on the inboard half of the wing, shortening the effective length over which twist was measured, which increased twist uncertainty.

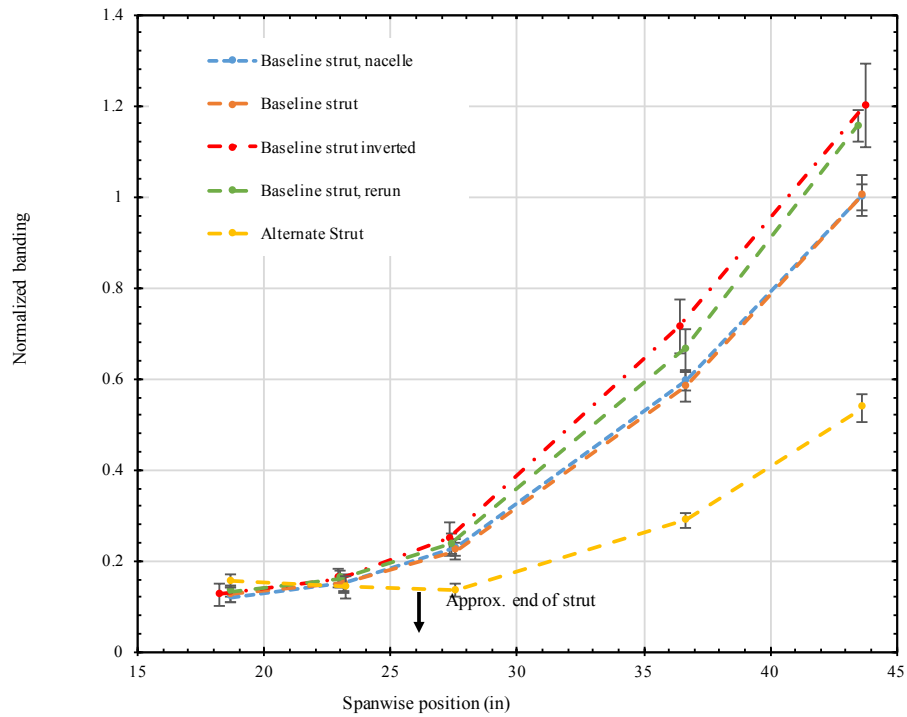Angle of attack was measured by photogrammetry for each data point as a by-product of the MDM

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Figure 4. Normalized bending (at trailing edge points) for multiple configurations at Mach 0.79, Re = 8.0 million per foot. Bending is calculated from a 10-image average. Normalization is with respect to the primary strut data.
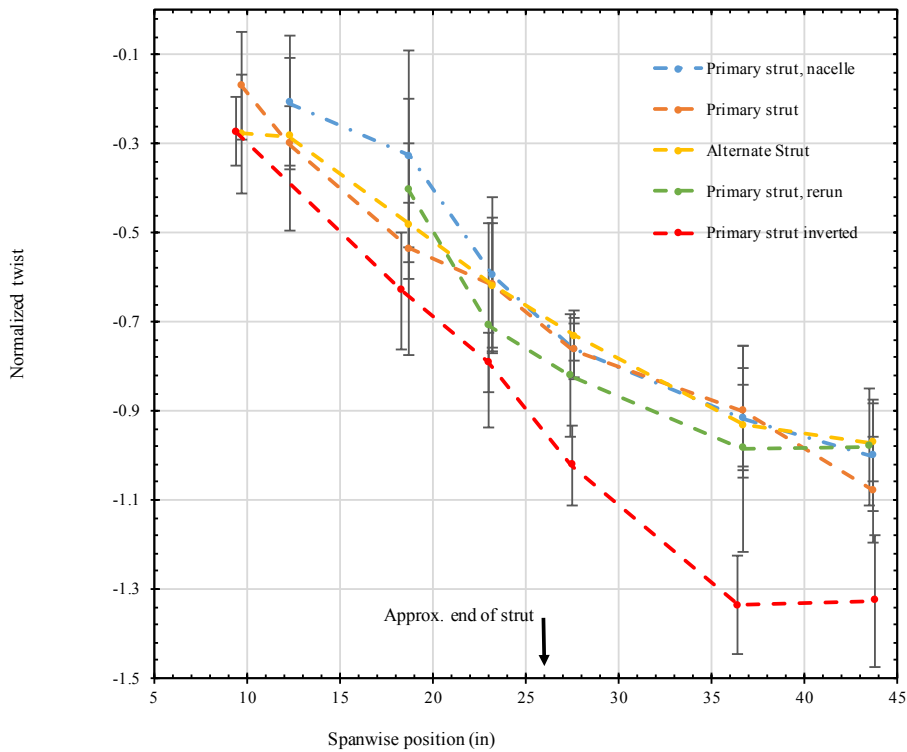

Figure 5.

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process. This measurement was compared to the value reported by the wind tunnel SDS for a single run and can be seen in Figure 6. The two measurements agree well with an RMS difference of 0.032°. This promising result is evidence of a future photogrammetry system with the ability to measure AoA to within 0.01°.

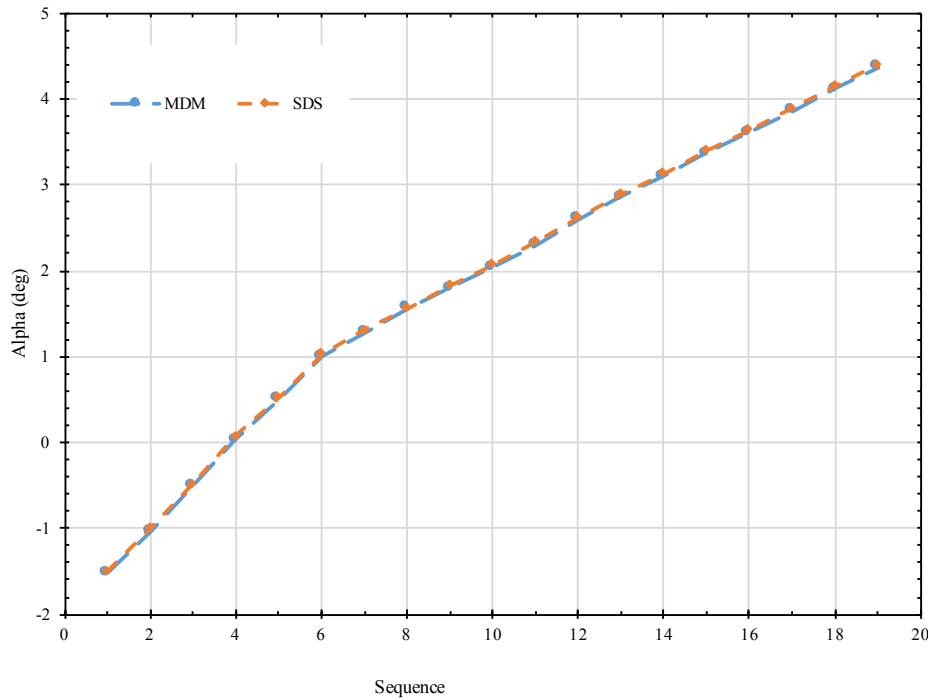For a full presentation of the photogrammetry results, see Drain et. al.[21]

Figure 6. Angle of attack as measured by the MDM system vs. the value reported by the wind tunnel SDS for a single run.

C. NASA Nozzle Plume/Shock Interaction Test

Photogrammetry was used to measure the position and orientation of a slender-body model during tests in the UPWT 9x7 SWT. The purpose of the test was to study interactions between an engine-exhaust plume, simulated by discharging compressed air through a nozzle at the aft end of the model, and shock waves created by a shock-wave generator mounted near the aft end of the model.[22] The model was tested "wings vertical" (to avoid the effects of flow angularity on AoA), so an accelerometer could not be used to measure angle of attack, and the support system did not include a balance, so the model position and angle, which were derived from encoder and resolver data from the model support system, could not be corrected for deflections due to aerodynamic loads. The model support system included two additional elements that introduced flexibility and increased the uncertainty in the model's posi-

Figure 7. NPSIT

tion and attitude: a linear actuator, which allowed the model to traverse upstream; and a thin swept blade, which offset the model axis from the axis of the sting.
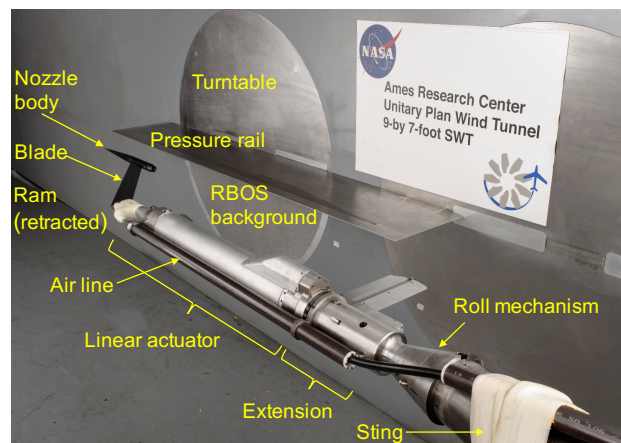
Figure 8 on the following page shows typical photogrammetry data from this test. The AoA measured by photogrammetry (symbols) and SDS (dashed lines) are plotted versus streamwise position for an "x-sweep" of the model at M = 1.6 and nominal AoA = 0°. Data are shown for three levels of blowing (nozzle pressure

ratio, NPR). The photogrammetry data show a linear increase in AoA as the model moved upstream whereas the SDS data indicated constant AoA. Blowing produced an offset in AoA data that increased at higher NPR.

For a full presentation of the photogrammetry results, see Schairer, et. al.[23]
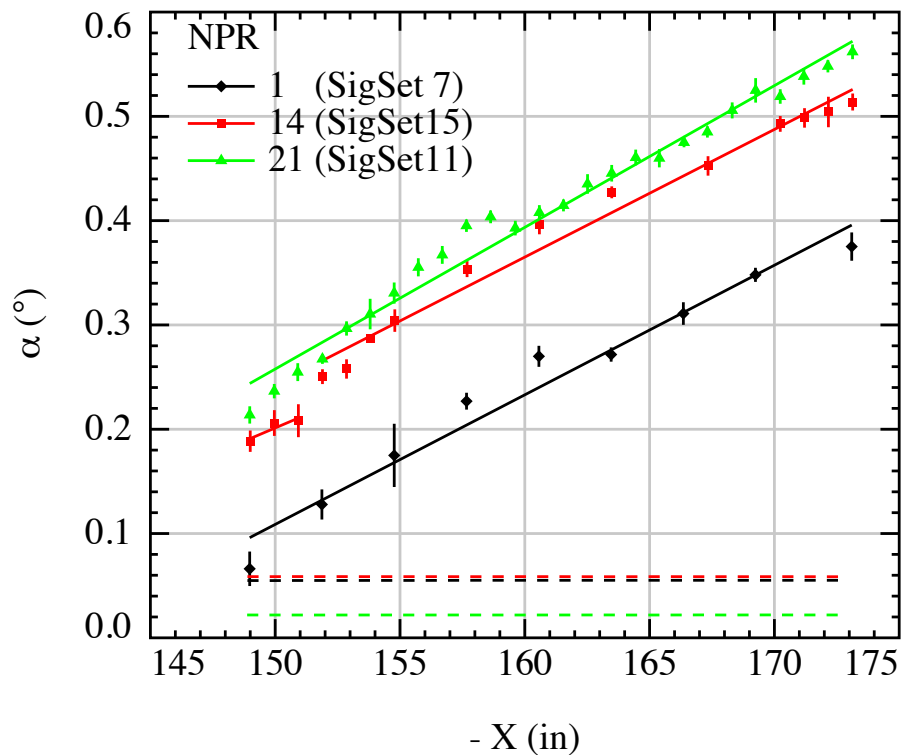

Figure 8. Angle of attack measured by photogrammetry versus streamwise position for different nozzle pressure ratios (NPR). Data are for nozzle body only; M = 1.6; alpha = 0; distance from pressure rail = 15 in. (NPR = 1 is no blowing).

V.   Future System Improvements

Though the photogrammetry system performed well and the required data were acquired, the system would benefit from changes to maximize performance. For MDM, much faster processing during the test is required. For OAoA, near real time turn around is required on processed data so that the information can be used to drive the model on the sting to a repeatable location in the tunnel. These requirements are both being driven by requests from customers with upcoming tests in the facility.

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One way to speed up data reduction is to increase the contrast of the images, which would improve target finding times. In an ideal image, the background would be all black and only the targets would be very bright white. This was a problem during both the TBW and NPSIT tests, as sufficient lighting was not available. Typically, photogrammetry is very successful with retroreflective targets, which increase the contrast between the background and the targets in typical images. However, retroreflective materials have an appreciable thickness to them which may trip the boundary layer on the model and adversely effect the flow. New speckling and targeting techniques are necessary that decrease the thinckness of the target and do not interfere with the boundary layer on the wing.

Another improvement that can increase the quality of the lights is to employ to high-power LEDs. Flash lamps that are sufficiently bright to adequately illuminate the targets typically have long rise times, making their refresh rate too slow for the required data acquisition times. Switching to high-power LEDs allows us to increase the illumination while keeping a short rise time.

One way to achieve higher contrast images without interfering with the boundary layer is by using fluorescent ink targets in conjunction with UV lamps and a low-pass filter on the cameras, which would block the UV and pass the fluorescent targets, thus cutting down on illumination of everything other than the targets. Initial bench-top and small research-level wind tunnel tests have shown this to provide high-contrast images.

Additionally, increasing automation for error flagging of targets and automatic discarding of bad points wold improve the system. Currently the system relies on the user to correct misidentified points.

Finally, a way to improve the system at the 9x7 test section would be to add windows further upstream than where they are currently located. During the NPSIT test, data at farther downstream positions had higher contrast than at farther upstream positions, due to the lack of optical access for lights upstream of the model's furthest upstream location. This meant that adequate illumination could not be provided on the nose of the model at the upstream extent. New windows are planned for this location as part of an upgrade to the UPWT at Ames called the "Test Section of Tomorrow".[24] This project will add windows in more locations and increase the optical area of existing windows, redesign the test section sidewalls for easier access and upgrade the electrical connections. These improvements will allow the MDM and OAoA to have adequate window space and decrease the likelihood of interference with other optical techniques that need optical access to the test sections, allowing the systems to be utilized for every test. Some of the improvements have already been achieved, such as the addition of new windows in the 11- by 11- ft. TWT.

VI.   Conclusion

Both AoA and MDM measurements can be made using an optical system that relies on photogrammetry to compute the needed measurements. Optical measurements are being requested by customers in wind tunnels with increasing frequency due to their non-intrusive nature and recent hardware and software advances that allow measurements to become near real time. These advantages have allowed the UPWT to choose a highly configurable optical AoA and MDM system based on photogrammetry to make the desired measurements. This system was recently exercised during two tests in the UPWT. System improvements are ongoing and will be implemented during subsequent tests.

Acknowledgments

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