AIAA 2001-0559

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39th AIAA Aerospace Sciences Meeting & Exhibit
8-11 January 2001
Reno, Nevada

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ABSTRACT

Two optical systems capable of measuring model attitude and deformation were compared to inertial devices employed to acquire wind tunnel model angle of attack measurements during the sting mounted full span 30% geometric scale flexible configuration of the Northrop Grumman Unmanned Combat Air Vehicle (UCAV) installed in the NASA Langley Transonic Dynamics Tunnel (TDT). The overall purpose of the test at TDT was to evaluate smart materials and structures adaptive wing technology.

The optical techniques that were compared to inertial devices employed to measure angle of attack for this test were: (1) an Optotrak® system, an optical system consisting of two sensors, each containing a pair of orthogonally oriented linear arrays to compute spatial positions of a set of active markers, and (2) Video Model Deformation (VMD) system, providing a single view of passive targets using a constrained photogrammetric solution whose primary function was to measure wing and control surface deformations. The Optotrak system was installed for this test for the first time at TDT in order to assess the usefulness of the system for future static and dynamic deformation measurements.

INTRODUCTION

Precise measurement of the drag coefficient of wind tunnel models using internal strain gage balances is highly dependent on the accuracy and repeatability of the system used to measure model attitude[1]. Proper resolution of the force components into lift and drag depends on precisely knowing the angle-of-attack of the internal balance. .

A 95% confidence level uncertainty analysis shows that an uncertainty in the drag coefficient of 0.0001 (one drag count) results from either 0.08% non-repeatability of the balance normal or axial force or from a 0.01° error in balance angle-of attack[2]

Currently inertial devices are the primary means to measure model attitude in most wind tunnels. However, inertial devices are insensitive to changes in angle when the plane of rotation is perpendicular to gravity such as occurs for vertically oriented models during semispan testing. In addition, inertial devices can exhibit large bias errors induced by dynamics (such as sting whip) that may require correction techniques in order to achieve the required uncertainties. Optical techniques are effective in virtually any orientation and are immune to the bias error due to dynamics, but to date are still not totally suitable for routine model attitude measurements in many wind tunnel facilities. A comparative analysis of the various techniques employed in this test will.provide future test a closer approximation to the model attitude uncertainty whether it is with inertial or optical devices.

TEST CONFIGURATION

The NASA Langley Transonic Dynamics Tunnel (TDT) is a closed loop, continuous return tunnel with a 4.9 x 4.9 meter test section. For this test the tunnel operated at Mach numbers ranging from 0.1 to 0.8. The test was conducted over various total pressures ranging from near vacuum to atmosphere. The facility, designed for aeroelastic research, can use air or heavy gas (R134A) as the test medium. The R134A gas, having a density much greater than air, facilitates wind tunnel model aeroelastic scaling. For this test configuration testing was divided between air and heavy gas.

Figure 1 shows the sting mounted full span 30% geometric scale flexible configuration of the Northrop Grumman Unmanned Combat Air Vehicle (UCAV) installed in the TDT facility. The retro-reflective targets used by the VMD system are distributed across the lower surface of the model and the active markers utilized by the Optotrak system are grouped near the center of the model.

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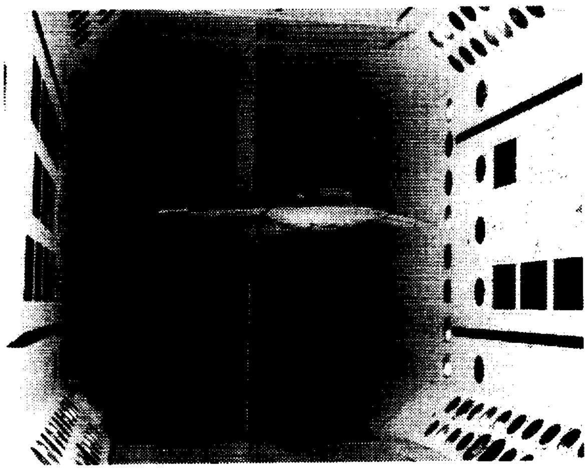

Figure 1. Northrop Grumman Unmanned Combat Air Vehicle (UCAV) installed in the TDT facility.

The testing provided a comparison of the performance of the two optical systems with the inertial devices whose results were obtained simultaneously. While the model was tested over an angle-of-attack range of –6° to 15°, interference from test section lights restricted the operational range of the Optotrak® system to -6° to 8°.
The approximate location of the measurement points on the model for each of the three systems is identified in figure 2.

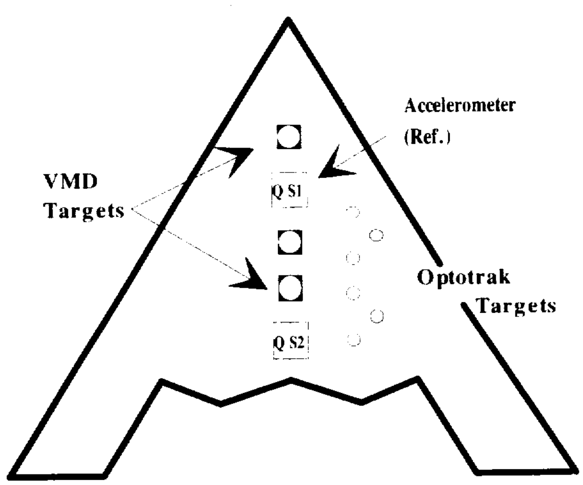

Figure 2. Model Measurement Positions.

SERVO ACCELEROMETER

Inertial devices have been extensively used in wind tunnel applications and packaged in a variety of custom configurations. Inertial devices can have large dynamic components; consequently it is necessary to pass the output through a low-pass filter in order to achieve accuracies of 175 micro-G's (0.01degree)[3]. For the comparisons here the inertial device will be used as reference for comparative analysis with of the Optotrak and the VMD data.

Two inertial packages were included in the fuselage, one slightly forward of the model center of gravity and the other aft of the models internal balance. The inertial package, based on a precision servo accelerometer has a pendulous flexure made from fused quartz[3]. The servo control mechanism, which includes the servoelectronics, is completely self-contained. The angle-of-attack is derived from the servo output required to keep the proof mass assembly in its balanced position when a force is applied. A diagram of the servomechanism and the internal components of the accelerometer are shown in figure 3. The accelerometer is packaged along with the electronics for both control and temperature compensation.

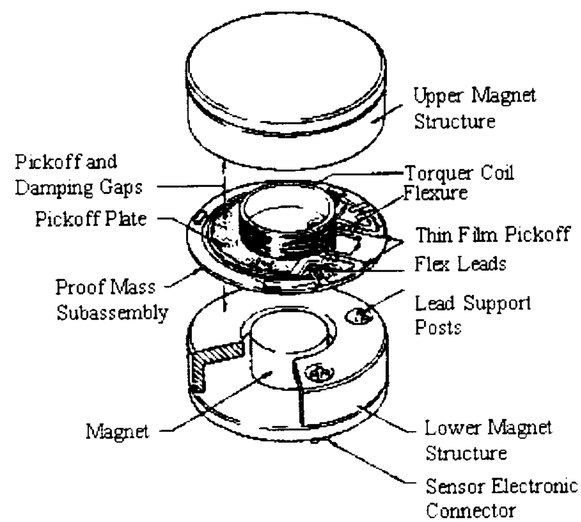

Figure 3. Precision Accelerometer (Exploded View)[2].

While the static laboratory calibration indicates highly precise results, the tunnel environment introduces variables, which have a critical influence on the error contribution. Stability, temperature sensitivity and rectification must be considered when addressing contributing factors to model attitude measurement accuracy. While stability is primarily determined at the time of manufacture, NASA Langley has developed a series of test to screen for those units only capable of meeting the measurement criteria [3]. The temperature characteristics of the accelerometers are considered as part of the selection process as well. The rectification characteristics of an accelerometer, (i.e. the generation of an erroneous dc output when subject to vibration), has proved to be the most difficult problem to solve[3].

Traditionally the accelerometer packages used to measure model attitude at NASA Langley facilities have been susceptible to errors generated through sting whip, a centrifugal acceleration caused by a dynamic pitching or yawing motion of the sting-model assembly. However, the packages used for this test, shown in figure 4, have incorporated additional accelerometers to measure these extraneous acceleration components. Once measured the appropriate corrections are applied through data reduction to correct for these error components[4].

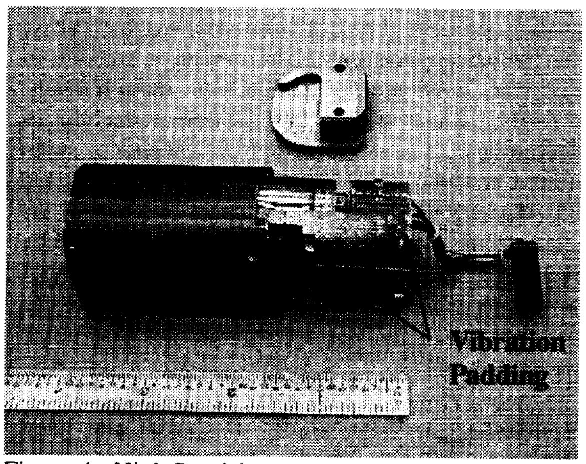

Figure 4. High Precision Accelerometer Inertial Measurement Package (Typical).

STATIC CALIBRATION

Laboratory calibration of the QS1 accelerometer package using a high precision (1 arc second) rotary index table with precision digital voltmeter produced a 95% confidence interval of ±0.000115 deg over an angle range of ±20 deg. A plot of the calibration for the QS1 package is shown in figure 5.

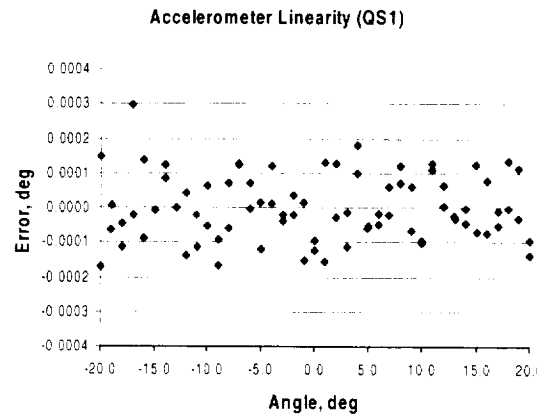

Figure 5. Static Calibration Ref. Accelerometer (QS1).

VMD MEASUREMENT SYSTEM

Videogrammetric Model Deformation (VMD) is a non-contacting optical technique primarily developed for wind tunnel model deformation measurements. The VMD technique is capable of providing accurate measurements of discrete targets placed on the model from which wing twist, bending and angle-of-attack (AoA) can be calculated.

The VMD camera, a standard video grade CCD camera with a 752x240 pixel resolution was located in a lower fillet of the test section wall adjacent to the Optotrak camera sensors. The general location of the VMD system relative to the model is visible in figure 6. The window glass that normally covers the housing port was removed for this test.

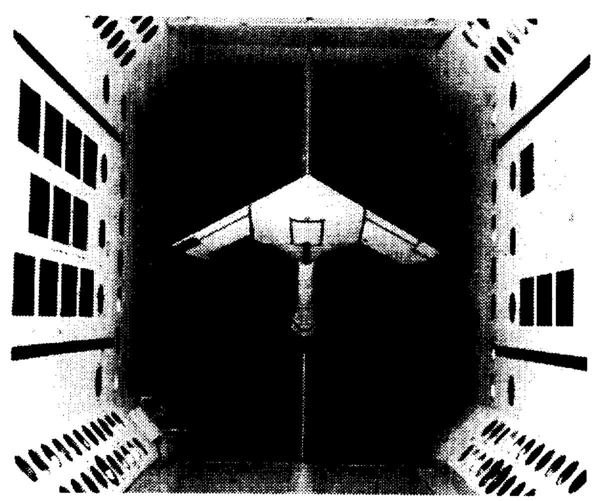

Figure 6. Optical System(s) Hardware Test Section Arrangement.

In addition to the retro-reflective targets that were placed along several spanwise locations of the wing for deformation measurements, a row of targets were placed along the lower fuselage serve as reference in the deformation measurements to reduce the dependence of the deformation data on sting bending. The retro-reflective targets, as shown in figure 7, provide high contrast imagery that greatly simplifies and increases the robustness of the image processing routines required to locate the target positions within the image plane to sub-pixel accuracy[5]. To insure the targets remained in the field-of-view over the complete angle of attack range a 12.5-mm focal length lens was used. For this test the VMD system acquired time-dependent deformation data at 60 Hz. rates.

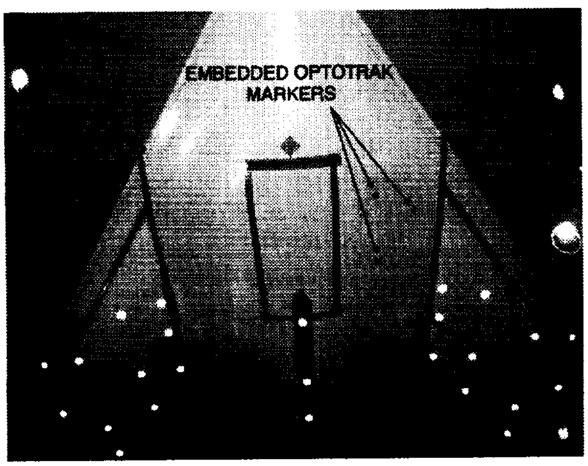

Figure 7. VMD System: Retro-reflective Targets.

VMD SOFTWARE

The VMD system uses a blob analysis technique for locating targets. Once identified, a target centroid is calculated with sub-pixel resolution. The system will record position data for the targets in near real-time. Anomalies in target-tracking may result from (1) bright surface reflections which interfere with a particular target in the image, (2) high-speed model motion which blurs the targets, or (3) loss of image due to severe lighting changes or obstruction in the viewing field[6]. Once acquired the software will convert target centroids to spatial coordinates. The deformation or angle of attack is then computed from the spatial coordinates.

CALIBRATION

The multi-step calibration of the VMD system was conducted in the tunnel test section; a custom 3-D calibration fixture with targets of known coordinates was positioned in the camera field-of-view such that it approximately filled the CCD image plane. A sequence of images were acquired while moving the calibration frame over a know distance, the image sequences were used to determine the internal camera calibration parameters (i.e. radial and de-centering distortion, and principle point location). An image sequence was also acquired with the calibration fixture aligned with the models coordinate system. This image sequence was used to mathematically align the VMD cameras coordinate measurement system with that of the model. As a final step the QS1 accelerometer package was used to validate the VMD measured angle over the entire angle of attack range without flow.

OPTOTRAK SYSTEM

The Northern Digital Optotrak® system is an off-the-shelf product that has been adapted for use in wind tunnel applications. The system is capable of providing 6 degree of freedom measurements primarily for use in the study of human motion, or Kineseology[7]. The system employs a series of small infrared emitting diodes [IRED], commonly referred to as markers that were embedded in the skin of the model. The system is currently being investigated by several aerospace organizations in addition to NASA for various wind tunnel measurements. The analysis here focuses on the performance of the Optotrak® system at the TDT.

The diodes are sequentially triggered and their images are focused onto a series of linear sensor arrays (each array containing 2048 pixels). Image centroids are computed and converted in the system software to object space position coordinates, which are then used to determine the position and orientation of the collective group of diodes.

The system has been used at three NASA facilities at the Langley Center for both sting mounted and semispan models, but has not to date been used for measurements other than angle of attack.
For this test six markers were placed on the model. System parameters controlled through software give the operator control over the marker voltage, strobing frequency, and duty cycle. The manufacturers documentation indicates the system is capable of monitoring up to 256 markers; this configuration has not been tested in any lab or tunnel configuration to date at NASA Langley[8]. Careful adjustment of the aforementioned parameters provides optimal visibility of the markers for the camera sensors. While the system provides the capability of strobing markers up to a maximum rate of 3500 Hz. for this test the optimum setting was identified as 1800 Hz.

A centroid algorithm is used to calculate the position of the markers to subpixel accuracy. For this test the six markers as grouped defined a rigid body, which was used to track the actual pitch motion of the model. The system provided updates of rigid body position at a rate of 50 Hz. to the host data acquisition system. Higher rates up to 100 Hz. are possible if the raw 3D (XYZ coordinates) data is transferred rather than rigid body positions. A standard 300 MHz. Windows based personal computer was used to acquire all data. An operator interface is provided through the system software for basic system control, on-off operation, calibration, diagnostics, and data communications with an external data system. General operations of the Optotrak® system do not require a detailed understanding of photogrammetric principles.

MODEL HARDWARE

For this test the six infrared LED markers were spread along a three-foot section of the models lower fuselage. A typical installation is shown in Figure 8. Laboratory testing has shown that optimum system performance is achieved when the markers are distributed over several feet of surface area. Marker placement must take into consideration model deformation and bending, since the markers are treated collectively as a rigid body movement seen by each of the markers must be uniform to prevent erroneous angle computations.

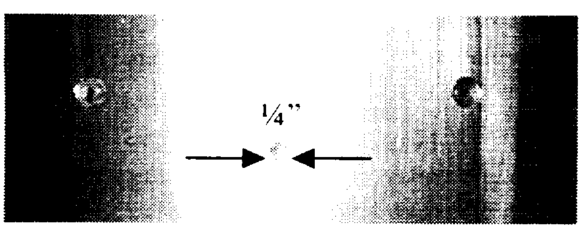

Figure 8. Embedded Infrared Emitting Diodes (Typical)

To prepare for installation of the markers a ¼" diameter through hole was drilled in the model skin. The markers were positioned such that their lens cover was 1/16" below the surface of the model. The internal wiring for the markers was routed to the strober package placed in an internal model cavity.

TUNNEL HARDWARE

Most of the system image processing hardware including the sensors was located in lower lighting fillets in the test section. Figure 6 shows the orientation of the system hardware to the model position. In addition, the system hardware located within the tunnel plenum required extensive pneumatic plumbing to support system cooling. The Optotrak® system also requires an in-line amplifier where distances between the markers and the system control unit exceed 100 feet, as was the case in this test configuration.

The Optotrak® markers operate near a wavelength of 840 nanometers. While the system is generally insensitive to most reflections, there was a problem from the strong source of infrared radiation present in the test section from incandescent lighting. The extent of the problem prohibited the acquisition of data at model angle of attack greater than +10 degrees. It was theorized that the model helped shield the undesired light source at lower angles.

SYSTEM CALIBRATION

The calibration method prescribed for the Optotrak® system has been common for all configurations tested at NASA Langley facilities. While the system is capable of providing both rotational and translation measurements along all three coordinate axis, the emphasis of this effort will focused on the axis representing the models local vertical plane (pitch). A calibration frame provided by the manufacturer is used to establish a global coordinate system and the relative positions of the sensor heads (cameras) to each other. The calibration procedure only needs to be repeated if the position of the sensor heads changes. For this case the global coordinate system was established by the calibration frame initially positioned coincident with the coordinate system of the model, in cases where it is impractical to perform such an alignment a transformation is required to align the global coordinate system with local coordinate system of the model.

A baseline static calibration derived from laboratory testing has shown the Optotrak® to have a 95% prediction interval of ±0.0035 deg over a range of –20 to +20 deg provided all movement is restricted to single planar motion. Measurements of true 3D motion have been shown to produce significantly less accurate data. These errors are attributed to errors in the coordinate transformation process in the system software.

COMPARATIVE WIND-OFF DATA

The accelerometer, Optotrak, and VMD systems wind-off data were acquired at various stages over the three-week period of the test. There were an extensive number of wind-off points taken at 0° angle-of-attack as shown in figure 9. A static comparison of the differences between the three devices was performed to provide an assessment of the data quality and general uncertainty that could be applied during the actual test runs. The wind-off differences between the accelerometer (QS1)/Optotrak, and (QS1)/VMD are plotted as a function of angle-of-attack and shown in figure 9. QS2 was a backup accelerometer package placed in the rear of the model fuselage; laboratory calibration indicated the QS2 package performance was slightly inferior to the QS1 package. The mean of the differences in each of the comparisons is not zero. The magnitude of the differences is on the order of 0.004° for the Optotrak system. The VMD system exhibits significantly higher variations with differences from the reference QS1 on the order of 0.015°. This higher variation is not to be unexpected since the system was not optimized for angle of attack measurements, but rather for deformation measurements of the wings and control surfaces.

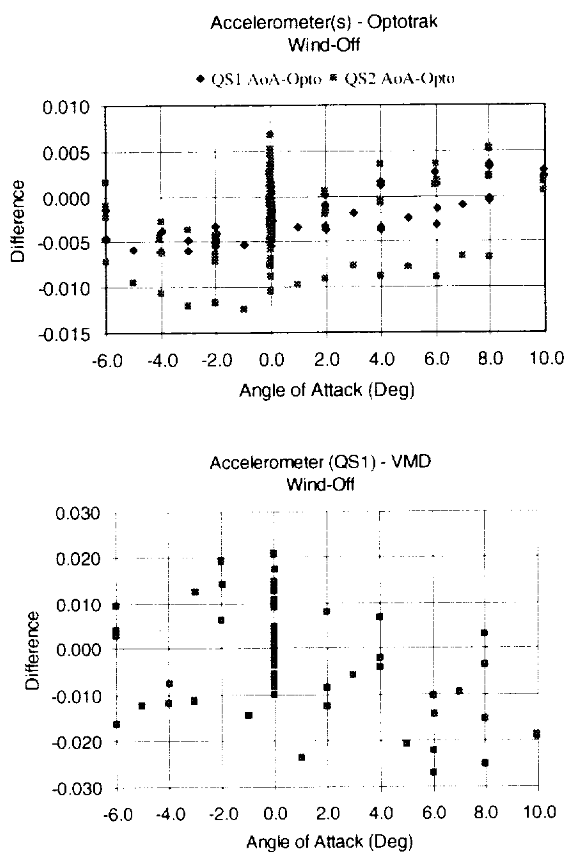

Figure 9. Wind-off Comparison(s).

COMPARATIVE WIND-ON DATA

Over the course of the test 1600 discrete data points were recorded under a variety of test conditions outlined in the test configuration section. The variation of the difference increased between the accelerometer and both the Optotrak® and the VMD system during wind-on conditions. A plot of all recorded data points for which Optotrak data were taken showing the variation in the difference for the angle of attack measurements is shown in figure 10. The higher concentration of data runs where all AoA measurement devices recorded comparable data occurred up to test point 500. The test medium was switched over to heavy gas at that point restricting the availability of Optotrak data due to lack of forced air cooling required by the Optotrak system.

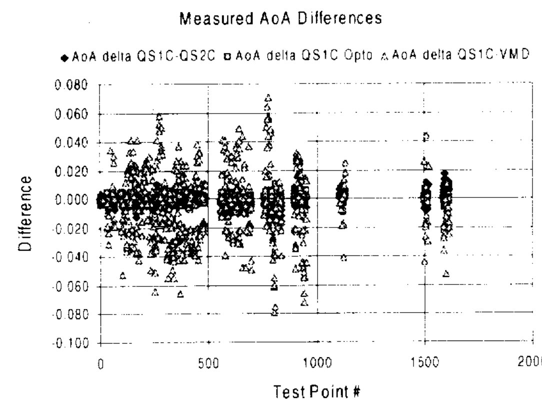

Figure 10. Measured AoA Variations.

The precision of the accelerometer/Optotrak data in figure 10 is overshadowed by the variation of the VMD data. The measured difference between the accelerometer and the VMD system exhibited a ±0.030° variation over the measured range of angle of attack, while the Optotrak maintained a variation on the order of ±0.004 consistent with the wind-off performance.

Figure 11 provides a closer inspection of the measured difference for the Optotrak system over the range of angle of attack for a sample population (Runs 13-37), which indicates the accelerometer/Optotrak variation to be ±0.003. The measured difference for the VMD technique over the same sample set indicates a ±0.03 variation. The differences for both comparisons are distributed randomly about a mean value that changes with each angle of attack.

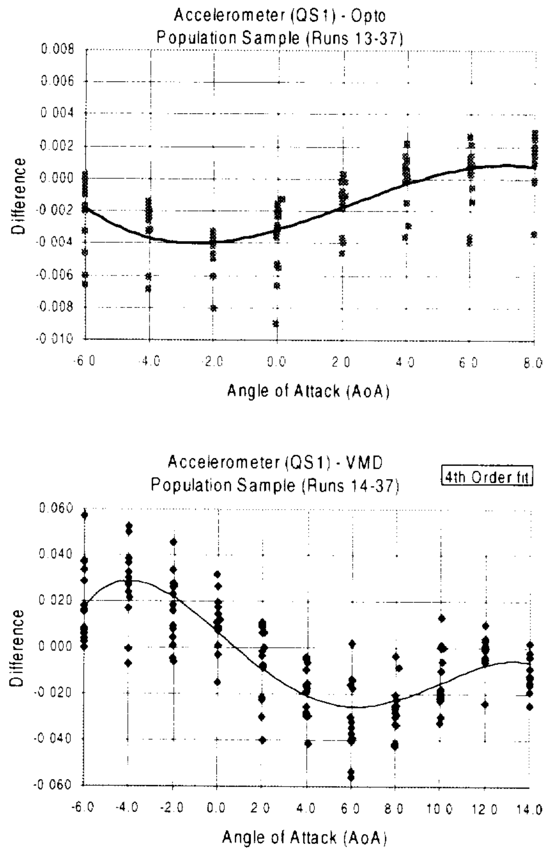

Figure 11. Difference Comparison Runs 13-37.

To resolve the differences between the accelerometer/Optotrak even further we look at all data collected for an angle of attack of 4°. The scatter is again consistent with the performance we have seen with the sample set of runs. The Optotrak maintained a variation of ±0.003°. Data for the alternate accelerometer is also shown in the plot.

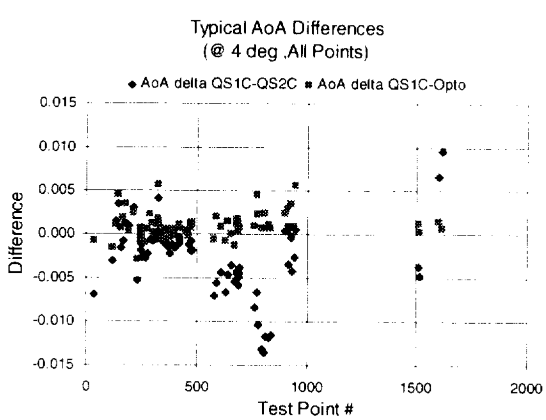

Figure 12. Optotrak Comparison at 4 Deg. AoA

Comparing the wind-on to the wind-off results indicates that the performance of the accelerometer/Optotrak is essentially the same for both cases.

The mean difference between the AoA measurement techniques for all test points is shown in figure 13. The mean difference variation present in the wind-on population sample is consistent with that found in the complete data set.

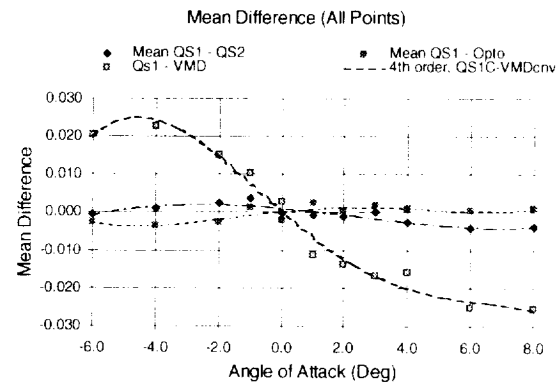

Figure 13. Mean Difference All Technique.

The standard deviation for the computed means provides an indication of the confidence interval for the Optotrak and VMD data over the range of angle of attack. The confidence interval represented by the 2• value for the Optotrak is ±0.005. The VMD system recorded a 95% confidence interval of ±0.020 over the same range. Figure 14 shows a plot of the standard deviation.

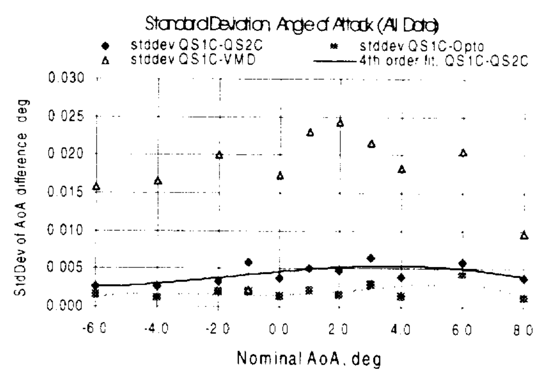

Figure 14. Standard Deviation All Techniques.

CONCLUSIONS

The ability to resolve the lift and drag components for models used in wind tunnel testing is highly dependent on the accurate measurement of model attitude (pitch).

When performing comparative analysis, as was the case for this test it is advantageous to have at least three different measurement devices on a test to identify anomalies unique to a particular device. Based on wind-on and wind-off comparisons of the Optotrak® with the Precision accelerometer and the VMD system, it is concluded that the Optotrak® performance in measurements in the pitch plane are comparable with that of the precision accelerometer. Measurements were in agreement with the reference inertial device to ±0.003 degrees with a 95% confidence level over the measured range. The performance characteristics for the three systems were comparable, the model and tunnel preparations required for the Optotrak system make that system less attractive for routine wind tunnel use. The Optotrak® system specifications indicate [7] the ability to provide true 3-D measurements, which can be used to calculate pitch, yaw, and roll, the significant drop-off in accuracy when measurements are recorded in the presence of true 3-D motion as determined in laboratory testing may make the system undesirable for some wind tunnel applications.

With the VMD technique using high contrast edge or high contrast wing targets, it is possible to make automated pitch angle or model deformation measurements with minimal impact on the tunnel and the model. While VMD offered less accurate measurements in terms of model angle-of-attack for this test, it should be qualified by stating that the row of targets for measuring angle-of-attack were located near the edge of the field of view and therefore susceptible to greater influence from lens distortion. If the system had been optimized for angle-of-attack measurements the performance would have been closer to that of the accelerometer and the Optotrak®. For this test the primary emphasis for the VMD system was on model deformation. The systems primary value stems from its ability to provide non-contacting model deformation measurements in situations where other on-board instrumentation would not be suitable. The VMD technique has been used successfully for model injection and sting bending measurements at hypersonic test facilities where it would be very difficult to make the same measurements with inertial or other optical techniques[5].

While optical techniques hold the promise of high precision 3D measurement capability, the accelerometer package is still the standard at wind tunnels including those at NASA Langley Research Center providing the highest precision for single axis model attitude measurement for wind tunnel testing. Recent advances in the accelerometer package now correct for the dynamic pitching and yawing motion of the model assembly (sting-whip), providing measurable improvements in most applications [4]. In test configurations where internal instrumentation is prohibited and certain semi-span configurations the inertial device may yield to other optical techniques, but under most applications the accelerometer package still provides the most robust and reliable technique for measuring model angle-of-attack (pitch) in wind tunnel testing.

ACKNOWLEDGEMENTS

Smart Wing is a DARPA/AFRL/NASA jointly funded program. The authors wish to thank the Northrop Grumman Smart Wing Test Team and the LaRC TDT staff for accommodating the needs required to obtain the Optotrak measurements

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[1] Steinle, F. and Stanewsky, E., "Wind Tunnel Flow Quality an Data Accuracy Requirements," AGARD Advisory Report No. 184, November 1982.

[2] Watzlavick,R.L.,Crowder,J.P.,Wright,F.L., " Comparison of Model Attitude Systems: Active Target Photogrammetry, Precision Accelerometer, and Laser Interferometer", AIAA 96-2252, 19th AIAA Advanced Measurement and Ground Testing Technology Conference, June 17-20, 1996, New Orleans, LA

[3] Finley,T.D.:"Model Attitude Measurements at NASA Langley Research Center", presented at the 30th Aerospace Sciences Meeting & Exhibit, AIAA 92-0763, January 6-9, 1992.

[4] Crawford, B.L. and Finley, T.D., "Improved Correction System for Vibration Sensitive Inertial Angle of Attack Measurement Devices",presented at the 38th Aerospace Sciences Meeting and Exhibit, AIAA 2000-0415, January 10-13, 2000.

[5] Fleming, G.A. and Burner, A.W., "Deformation measurements of smart aerodynamic surfaces", paper No. SPIE 3783-25, presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, July 18-23, 1999, Denver, CO.

[6] Burner,A.W. ,Radeztsky,T.H., Liu,T., "Videometric applications in wind tunnels", paper No. SPIE 0277-786, presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, July 30-31, 1997, San Diego, California.

[7] Stone, M., "Direct Articulatory Measurements", Acoustical Society of America, Woodbury, N.Y. 1993

[8] Northern Digital Inc. staff, "Optotrak®: System Guide-Version 1.0.1", Waterloo, Ontario, Canada, December, 1994, Copyright © 1994.