Technology Review of Wind-Tunnel Angle Measurement

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Angle measurements are fundamental measurements in wind-tunnel testing, and are integral for most, if not all, wind-tunnel tests. Aerodynamic tests generally rely on angle or attitude measurement for research or testing objectives with demands of high accuracy and repeatable measurements. This paper reviews historical and recent developments in wind-tunnel angle measurement systems. The review covers sensor technologies including on-board and off-body measurement solutions. On-board sensor solutions, such as accelerometers, gyroscopes, and electrolytic bubbles, are compared with off-body solutions, such as laser interferometers and photogrammetry. Benefits, use cases, and limitations for each of the technologies are discussed to help guide wind-tunnel user selection, and provide direction for further research in sensor technologies which may provide enhanced measurement capability.

Nomenclature

AEDC	Arnold Engineering Development Complex
AoA	Angle of Attack
BTWT	Boeing Transonic Wind Tunnel
DLR	German Research Institute for Aviation and Space Flight
DTG	Dynamically Tuned Gyroscope
ETW	European Transonic Windtunnel
FOG	Fiber-Optic Gyroscope
LAM	Laser Angle Meter
LaRC	Langley Research Center
MEMS	Micro-Electro-Mechanical Sensors
NASA	National Aeronautics and Space Administration
NLR	National Aerospace Laboratory
NTF	National Transonic Facility
OML	Outer Mold Line

I. Introduction

The scope of this paper is to gather and centralize knowledge of angle measurement in order to help facilitate future technology development at NASA Langley Research Center (LaRC). The area of focus for this paper is on angle measurement technology applied to ground-based aeronautic testing, where pitch, roll, and yaw angles of an aerodynamic model with respect to a wind-tunnel test-section are desired to be known for aerodynamic analysis. The available volume of wind-tunnel models varies widely between the ranges of aeronautic testing, from large low-speed models to small supersonic and hypersonic models. Due to this range of model sizes, the approaches for angle measurement changes for each type of testing. For example, supersonic testing tends to utilize off-body measurements, such as photogrammetry, or potentiometers and encoders built into the support structure. Whereas larger models will accommodate single- to multi-axis accelerometers within the body.

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Accuracies and reliability of force measurement depends partially on angle measurement. Model attitude estimates are used to translate force balance outputs from the body-axis to the wind-axis for aerodynamic analyses. This relationship couples the angle and balance measurements into the overall uncertainty of wind-tunnel data. It is widely accepted that drag measurement is the limiting factor on force and angle measurement accuracies. In the 1980s the drag requirement for small model changes was decreased to a ΔC_D of 0.0001, which leads to an angle of attack accuracy of 0.01°.[1,2]

This manuscript is divided into different technology sections that detail the literature search for each. Each section will discuss the developments, testing, and outcomes of the various techniques. The main technology sections in this paper are; inertial measurement, photogrammetry, and other off-body optical techniques. Concluding remarks and summary of the technologies will be presented to help guide future research.

II. Inertial Measurement

This section will discuss sensor technology that uses inertial references as a medium. Gyroscopes, electrolytic, and accelerometers are discussed since they rely on inertial forces as the principle of operation. Inertial forces can act as gravity or acceleration due to sensor movement.

II.A. Electrolytic Tilt Sensors

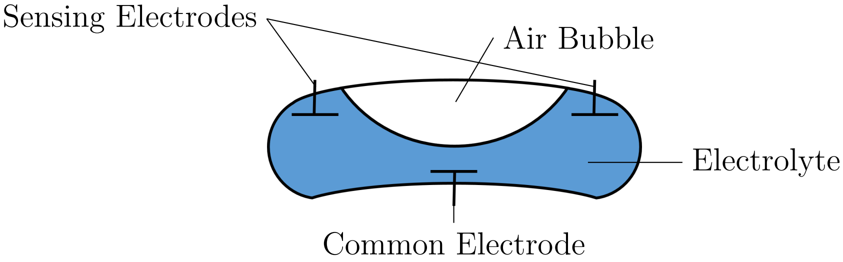

Figure 1. Electrolytic Tilt Sensor Outline

Electrolytic tilt sensors are sealed curved-glass cylinders with electrolyte, electrically conductive fluid, and several electrodes (Figure 1). Two sensing electrodes are placed at the tips of the cylinder and a single, common, electrode is located in the middle. As the electrolytic sensor is pitched, a captive bubble causes an imbalance between the two sensing electrodes. A single conditioner provides an AC voltage for the sensor, and demodulates the sensor output to an amplified DC output voltage. Calibration of the output voltage to sensor angle is used to convert the signal into an angle measurement.

Wong originally studied the feasibility of using electrolytic sensors to replace servo accelerometers.[3,4] In a study eight-electrolytic sensors were tested for; sensory sensitivity, linearity, repeatability, hysteresis, temperature characteristics, roll-on-pitch interaction, lead-wire resistance sensitivity, step response, and rectification. Testing results revealed that the electrolytic sensors are an order of magnitude worse than Q-Flex accelerometers in terms of angle measurement.

Wong further studied the use of electrolytic sensors to replace wall attitude sensors at LaRC's National Transonic Facility (NTF).[5] Due to cryogenic temperatures of NTF, these sensors were placed in heated enclosures to maintain a internal temperature of 160 ° F. Testing results showed that the assembled package did not meet the required ±0.01°, but did meet a larger ±0.1° requirement for less harsh environments.

Electrolytic sensors were implemented along side Q-Flex accelerometers in several angle of attack (AoA) packages at LaRC. In this arrangement, electrolytic sensors were utilized for setting wind-tunnel wind-off and -on zeros.[6] Current AoA package design no longer feature electrolytic tilt sensors, and solely rely on the Q-Flex sensors for re-leveling. These sensors are still utilized for re-leveling balance calibration fixtures at LaRC's force measurement laboratory. Electrolytic tilt sensors provides a cost effective re-leveling platform with a total sensor and signal conditioner cost of approximately $1,400 USD.

II.B. Accelerometers

Accelerometers are typical choice for angle measurement, due to their high accuracy and good repeatability and are widely used at many different facilities. Accelerometers typically measure the movement of a proof mass on a cantilever beam, where the deflection of the beam is a function of the acceleration. Due to being gravity based, only pitch and roll angles can be measured, since yaw would be about the gravity vector.

Use of accelerometers for AoA measurement dates back to the 1940's, when oil-damped, open-loop, strain-gaged cantilever accelerometers were used.[6] These oil-based accelerometers had issues with leaking oil and air bubbles; the units were also large, and were further refined into the 1960's. In the 1970's a new accuracy requirement of $\pm 0.01^\circ$ for wind-tunnel testing required a new type of sensor to be developed. The first type of technology studied was the servo accelerometer which once evaluated had large rectification error that did not allow for wind tunnel use. Rectification error is when the output of the sensor is biased due to high frequency vibration near the natural frequencies of the sensors internals. A second generation sensor, a pendulous metallic flexure, oil damped, design, was smaller in size with a natural frequency of 200 Hz. Unlike the original oil-damped accelerometers, these updated packages did not leak. One issue that was discovered with the second generation sensor was the tendency to oscillate with long cables.

The latest generation, and still used today, are pendulous flexures made from fused quartz, also known as Q-Flex. These have a natural frequency of over 1000Hz. Extensive testing of the Q-Flex sensors was conducted to ensure that these sensors performed as required. Testing results showed low temperature effects, good stability, and low rectification error. Installation of isolation pads around the Q-Flex sensor reduces the rectification error by a factor of 400.

NASA LaRC developed a transferable mobile standard called the Angle Measurement System (AMS) devised of three orthogonal Q-Flex accelerometers in the 1990s.[7] Improvements were made to the AMS by incorporating sensitivity and bias shifts due to temperature. This compensation applies quadratic fits to the bias and sensitivity shifts, which reduces errors to below $\pm 0.01^\circ$ for temperatures ranging from $70\,^\circ$F to $120\,^\circ$F.

Calibration improvements were made to both a base Q-Flex sensor and the LaRC AMS package by Tripp el at. and Marshall el at., respectively.[8,9] Both improvements were based on solving for exact solutions of a coordinate transformation between the calibration table base and the sensor. Previously, simplified direct solutions were implemented that had approximation errors. For the Q-Flex calibration, the residual pitch errors were reduced from errors up to 0.028° to under 0.001°. For the AMS system it was shown to reduce the calibration residuals to ± 0.001 from ± 0.002, while reducing the systematic errors of the approximate solution.

II.B.1. Stingwhip

One issue found that affects all accelerometers is the phenomena of stingwhip. Stingwhip is where model, balance, and sting vibrations generate centrifugal acceleration that will bias sensor outputs. At LaRC's National Transonic Facility (NTF) model vibrations were found to significantly affect Q-Flex outputs.[10–13] Young et al. observed significant bias errors, up to 0.5°, during laboratory vibration testing of a full model, balance, and sting.[14] A first-order correction was developed based on known radii distances of the accelerometer to the center of rotation, and vibration magnitude measurements. This method was time-consuming, since a vibration study must be conducted for every model and potentially all model configurations prior to wind-on tunnel operations.

Buehrle et al. further developed the stingwhip corrections by summing the contributions for each vibration mode.[15] Laboratory testing demonstrated a reduction in stingwhip error for the first mode in the yaw plane from -0.146° to -0.009° and in the pitch plane (z) from -0.175° to -0.006°. This method of correcting for rectification errors also requires estimating the radii of each vibration mode experimentally for each model, balance, and sting combination. Additionally, an optical AoA system was utilized as a secondary angle measurement to measure any movement of the model during testing. Results from the video system were not adversely affected by the model dynamics.

In the late 1990's, NASA LaRC developed multiple stingwhip packages, QS-1 and QS-2, to provide real-time corrections.[16] Each of these packages featured extra sensors that accompanied a Q-Flex to measure the extra information required for stingwhip corrections. The QS-1 package utilized extra accelerometers to calculate the angular-rate of the AoA package, whereas the QS-2 measured the angular-rate directly with gyroscopes. The QS-2 package was laboratory tested against an Optotrack and photogrammetry systems.

Results from the test showed good agreement between the QS-2 and both optical systems when stingwhip corrections were applied. Wind tunnel testing at LaRC's 16-Foot Transonic Wind Tunnel showed similar results between the QS-1 and QS-2 packages given the different placements in the model.[17]

II.B.2. MEMS Based

Micro-Electro-Mechanical Sensors (MEMS) are an attractive option for attitude measurement, due to their small size. Kahng et al. performed laboratory testing of MEMS based capacitive and servo accelerometers at NASA LaRC.[18] Calibration information, and rectification errors for the MEMS sensors tested are shown in Table 1. Sine rectification testing was in the sensitivity axis over a frequency range of 20 to 5000 Hz. From these results, the capacitive sensor had approximately double the sensitivity of the MEMS servo-accelerometer, but suffers more that double the rectification error. Laboratory calibrations of these sensors showed error margins better than ±0.04° with a 95% confidence interval. These error margins do not satisfy the typical desired accuracy of sub-0.01°, but could be use where measurement capability does not exist due to size limitations.

Table 1. Calibration Data of AoA Sensors[18]

Type	Sens. (V/g)	Zero Bal. (V)	Linearity (% Span)	Rectification Error Sen	 0-deg	 90-deg
Servo	0.190	-0.346	±0.2	-0.34	-0.03	-0.10
Cap.	0.410	0.032	±0.3	1.00	0.20	0.20

Newman and Yu investigated a MEMS based attitude measurement system that is compact enough to fit within small high-speed testing models, where model volume is limited.[19, 20] The authors state that the requirements for this type of testing is not the typical ±0.01° but a more lax ±0.1°, and is achievable with MEMS sensors of the time. A prototype system of MEMS based accelerometers and gyros was tested on a calibration table. Results confirmed that the tested accelerometers are capable of meeting the ±0.1° accuracy requirements, but could not be confirmed for the gyroscope sensors.

More recently, Crawford and Rhode designed and built a MEMS based accelerometer AoA package for the 31-Inch Mach 10 Tunnel at LaRC.[21] This system comprised of two pairs of MEMS accelerometers with different sensing ranges, 3-g and 10-g. The pairs were wired in series to form a voltage differential to provide a near zero voltage at zero angle and to help compensate any temperature effects. Laboratory testing of the 3g sensor showed two-sigma performance of 0.025° and 0.009° over ranges of ±60° and ±24°, respectively. Wind-on testing with this package showed that an offset existed for the 10-g sensors based on comparisons to the 3-g sensor and tunnel encoder. The 3-g sensors performed on the order of the tunnel encoder, and did not see large changes with slight increases in sensor temperature. The lack of a functioning optical system for independent review of the encoder or accelerometers precluded any definitive absolute accuracy results and conclusions.

II.C. Gyroscopes

Gyroscopes are similar in principle to accelerometers where a proof mass system is designed to respond to angular rates instead of linear acceleration. Since gyroscopes do no measure angle directly, the signal must be integrated over time to yield an angle estimate. Typically, integration of the angular rate will start after the gyroscope is leveled by angle sensors or levels.

The earliest usage of gyroscopes in wind-tunnel testings dates to the late 1970s in a dynamic motion model.[22–24] Wind-tunnel testing of hypervelocity bodies was studied for motion on aerodynamic moment characteristic coupling effects. It was described that flight quality three-axis gyroscopes were used in the model. Chrusciel states that angle of attack measurements agreed well with data from a 3 Degree of Freedom dynamic balance, with corrections for gyro drift. Although, no accuracy values were claimed, it was noted that the data was sufficient for their analysis.

Fiber-optic gyroscopes (FOG) are popular in flight-vehicles and marine ships for there precise angular rate information, and lack of sensitivity to vibrations and accelerations. German Research Institute for Aviation and Space Flight (DLR) tested a FOG[25] as an replacement for accelerometers in order to avoid rectification and stingwhip errors discussed in the accelerometers section. DLR installed a off-the-shelf FOG into an Airbus A321 model that included a conventional accelerometer. FOGs tend to have random walk, and measurement drift issues, which could lead to large bias errors with increasing time. Stronzel developed an algorithm that helps mitigate these errors by adjusting the integrated angle with force measurement data. The basis of the differential inertial measurement technique (DIMT), is that the measured angle at two identical normal force measurements should be the same and the algorithm forces the second reading to agree with the first. For this process, upward and downward pitch polars are required to have more than one normal force replicate. The results from wind-tunnel testing, showed that the gyro and DIMT performed one order of magnitude better than their conventional accelerometer system. However, the results shown do not meet the required 0.01° resolution, and it does not appear that their conventional system has stingwhip corrections.

Dynamically tuned gyroscopes (DTG) are a cheaper alternative to FOG, which use a spinning rotor suspended by flexure pivots. Typically, DTGs can provide dual axis measurement about a plane normal to the axis of rotation. The Boeing Company developed a measurement package that utilizes a pair of DTGs, an electrolytic sensor, and a servo accelerometer.[26,27] From multiple calibrations it was found that the gyro had a sensitivity stability of approximately ±0.1%, which was deemed acceptable. Drift of the sensor was apparent, 0.08° over a 50 second run, but was corrected with measurements of a post run wind-off angle measurement from an accelerometer. Wind-on testing of the system showed that there is potential in the concept.

Further testing of the Boeing Gyro Attitude Position System (GAPS) was conducted at AEDC Tunnel 9 Test Facility in July 2007.[27] The system was tested at various pitch rates ranging from 8 °/s to 80 °/s, which is representative of the pitch rates used during testing at Tunnel 9. Wind-off testing showed that the total uncertainty of the results range from 0.05-0.1 deg, based on the difference between the gyro and potentiometer based measurements.

III. Optical Measurements

This section will focus on various optical methods that including photogrammetry, laser based systems, and other optical based techniques. Optical techniques are sought after for their independence from model vibration induced errors that inertial based measurements suffer from. Typically, most optical techniques rely on inertial sensors for the initial calibration of the system.

III.A. Photogrammetry

Photogrammetry is the most often utilized optical attitude measurement technique, and generally relies on more than one camera. A pair of cameras are placed at different view points, typically 60° to 90° convergence angle for highest accuracy, to triangulate points of interest on the wind tunnel model. These systems track points that are either self-illuminated or reflector based.

Several self-illuminated systems that have been developed are ELOPTOPOS by SAAB, Optotrak, and RADAC by CERT.[28–31] Many of these systems perform well, the ELOPTOPOS system claimed to have a resolution of 0.0026°, and a repeatability of 0.005°, and performed best without any roll or yaw angle.[32] The Optotrak system, still commercially available, has been proved to provide similar results to other systems such as Q-Flex accelerometers and a Boeing laser system, discussed later.[33] This system was also leveraged to provide yaw measurements at LaRC's 14- by 22-Foot Subsonic Wind Tunnel with good agreement to the model support system.[34] Most of these systems were are not widely used because they require a calibration by another sensor and LED targets in the model outer mold line. These systems also require model dependent calibrations, due to change in LED positions between targets, which is also an issue with other photogrammetry techniques.

Retro-reflectors have been widely used as targets in photogrammetry installations.[35–39] Similar to self-illuminating targets, cameras track several bright reflectors on a model to triangulate the various positions. These systems have the ability to track all six degrees of freedom (DOF) such as the system used at LaRC's 20-Foot Vertical Spin Tunnel (VST).[35] With the increase in DOF the systems accuracy decreases, the first system at VST had pitch and roll accuracies of ±0.5°, and yaw accuracy of ±1.0°. Accuracies are better with reduced DOFs and a smaller test volume as evidenced by testing at AEDC's 16-Foot Transonic Wind Tunnel.[36,37,40] At AEDC an eight camera system was developed, but only two cameras were used for attitude measurement, the others were for pressure sensitive paint viewing. Ruyten demonstrated that the system had discrepancy from traditional measurements of ±0.06°, where most of the errors are attributed to camera and tunnel wall movements. In subsequent tests, improvements including lens corrections and new algorithms were made, although the system performed a factor of four worse than a previous test. This degradation in performance is attributed to a larger model requiring wider angle lenses with more distortions.

Tunnel lighting can play a major role in the performance of photogrammetry techniques. Model glare or glint can disrupt the data reduction process. An installation at LaRC's 31-Inch Mach 10 Tunnel used polarized lenses and lights to prevent glint from light sources.[38,39] This system used reflective targets and achieved laboratory predictions withing ±0.057° (95% prediction interval) for pitch. Roll and Yaw both observed a bias and sensitivity error, respectively, and would require more work to meet a ±0.1° accuracy requirement.

Other photogrammetry systems relied on high contrast between the model and the tunnel walls[34,41] At NASA's NTF, a system was developed to determine the slope angle and intercept of an edge, by linear least squares fit to several points along the model body's edge. The system was compared to two accelerometers, one onboard and another in the model support system. Results from wind-off testing showed that there was good agreement between the three systems, with offsets of 0.01°. The paper shows results from a wind-on run at tunnel temperatures of $-185\,^{\circ}$F and $-250\,^{\circ}$F. From these runs it was seen that the video system and arc-sector measurements agreed well, but some discrepancies exist with the onboard accelerometer. DLR developed a system that used a line CCD to view different sections of a model, and determine the angle of attack by model silhouette. The system relied on a strong contrast by back lighting the model which provided strong dark-light steps in the line CCD output. The system was able to measure models with high roll rates up to $3200\,^{\circ}$/s with resolution better than 0.5°.

In most photogrammetry techniques, the relative positions of the targets to the model reference point should be known with good accuracy. Martinez el at. demonstrated that they can be placed in random locations[42] on a model. Since random markers are used, consecutive images are compared to track target movement. Test results indicated significant jitter in the pitch and yaw measurements, but lack of precision roll control leaves the true accuracies unknown.

A novel technique was developed by Lie el at. that used an array of laser lines to illuminate a free falling target in a wind tunnel with self illuminating markers.[43] In this system, a self-illuminated target was placed at the rear of a falling axis-symmetric store to estimate the model centroid with the laser marks on the body. Mean-square error of the system are 0.12°, 0.14°, and 0.80° for pitch, yaw, and roll angles when compared to free fall estimations. Roll angle being the worst performer due to the small diameter of the body.

III.B. Laser Based Methods

This section discusses various uses of lasers in attitude measurement. Lasers are attractive since they provide a thin beam source that can be used to estimate changes in distances using interferometry.[44,45] The interferometry technique uses light reflected from two or more retro-reflectors to get differential distance readings between the two. It was found that the interferometer used had comparable or better resolution than convention methods of the time. Interferometry techniques are limited to the light return from a retro-reflector, which was shown to be 30° for sufficient light return. Zeringue tested the concept on a oscillating beam, not on an actual model, with results showing only good frequency response of the laser system.

Boeing Commercial Airplane Co. developed the laser angle meter (LAM) for use at the Boeing Transonic Wind Tunnel (BTWT) back in the late 1970s and early 1980s.[46,47] This system implemented a fringe-counting laser interferometer technique to measure differential angles between ±20°. The LAM system required a retro-reflector assembly to be installed into the model. The placement of the retro-reflector required a window on the models OML. During testing at the BTWT, an in-situ calibration was accomplished by a theodolite, and is required for each model installation. Operational testing of the system revealed that their sting deflection method did not provide the correct deflection beyond approximately 65% load. The system claimed to have a resolution of 0.005°, and calibration data showed an approximate root mean square error of 0.002°. The system is also greatly affected by single dropouts, since it relies on counting the full phase shift every 0.12°. If single dropout occurs, the counter has to be reset to a known angle, which potentially can lead to extended tunnel time.

Further development of the Boeing LAM is detailed by Pond regarding use at for NASA Langley Research Center in several contract reports.[48–50] Pond discusses the potential to build a two-axis system for the National Transonic Facility (NTF) by spatially separating the focal plane of the collimating lens, and by using orthogonally polarized beams. A two-axis breadboard test bed showed errors within ±0.01°, but no mention of measuring roll and pitch simultaneously.

Testing at LaRC's 0.3-m Transonic Cryogenic Tunnel (TCT) for optical distortion due to beam refraction found that fringe angles of 0.25° or less may lead to single dropouts. This was used to develop a system installed at the 8-Foot Transonic Pressure Tunnel that used a full phase shift angle of 0.24°. The system was demonstrated to cope with the test environment of the 8-ft pressure transonic wind tunnel, with no dropouts. Ames Research Center operated a LAM system at the 11- by 11-Foot Transonic Wind Tunnel (11x11 TWT).[32] This system required a linear motion system to allow the model to be tracked by the LAM system. The 11x11 TWT required the LAM to measure what would be considered yaw, since a floor mounted semi-span was tested.

Watzlavick el at. performed a comparison test of three measurement systems; Q-Flex accelerometer, Optotrak, and Boeing Laser Angle Meter.[33] This comprehensive study tested the systems using three different mounting techniques; straight sting, upper swept strut, and a plate mounting. Results from wind-on testing showed that there were no large differences between any of the three measurement techniques. All three systems were capable of meeting the ±0.01° requirement for the tunnel conditions tested.

From the comparative study and the possibility of signal dropouts, it seems that the system fell out of use because it did not add any extra benefit over Q-Flex sensors. Another issue with the LAM system is that it is sensitive to movement of the laser stand due to temperature changes, an issue mostly seen at cryogenic facilities. Currently, no LAM system is in use at any NASA facility.

A unique laser based system was a yaw meter developed by The Royal Aircraft Establishment, part of the United Kingdom Ministry of Defence.[51] This system consisted of a sweeping vertical-laser fan, created by a rotating cylindrical lens, and several photo sensors in the model. An encoder on the rotating cylindrical lens is recorded every time a photo sensor is illuminated by the laser, which provides the necessary information to calculate yaw given a distance between two photo sensors. This system is very similar to that of the HTC VIVE virtual reality system, which will be briefly discussed later.

III.C. Other Optical Methods

This section will discuss different optical or light methods that were tested.

McDonnell Aircraft Co. in the 1980s developed a novel angle sensor based on the principles of polarized light.[52] This system used a pair of on-board light sensor that measured changes in light intensity as a function of AoA, due to the changing angle of an on-board polarized filter. From a calibration study of the infrared model angle position sensor (IMAPS), a 95% confidence interval of 0.04° was found over a 7-day period. Since this sensor requires light to be pointed at a certain spot on the model, the model cannot be rolled or have significant movement. Testing of this sensor at AMES 11x11 TWT found that fluorescent lighting at the facility induced errors in the system.[32]

Another novel optical sensor was developed by Complere Inc in the 1990s.[2, 53] This system is based on the displacement of a beam due to refraction of a transparent material. This method used a two-axis lateral effect photodiode to track the displacement of the light spot. A expanded and collimated laser was used as the light source to provide near constant light in a certain region. Two sensors were originally developed with ranges of ±10° and ±20°, which had accuracies of 0.01° and 0.03° for each sensor respectively. With this setup, a laser light source would have to track the model to ensure the sensor is always in view of the light source, if model movement is significant during pitch motions.

The Complere sensor was further tested at Ames 14-Foot Transonic and 9- by 7-Foot Supersonic Wind Tunnels. Calibrating the sensor with a theodolite at 7x9-ft facility showed that accuracies of 0.006° were possible for wind-off conditions. Tests conducted at 14-Foot showed that the sensor was not sensitive to vibrations as an inertial sensor would be, but was affected by wall movements resulting in errors as large as 0.1°.

The European Transonic Windtunnel (ETW) also developed an optical pitch sensor called the Model Attitude Measurement system (MAMS).[54] This system is similar to that of the Boeing LAM, where light from LEDs is reflected by a corner cube and returned to an optical sensor. Model pitch angle is calculated from the diffraction phenomenon due to a grating on the corner cube. This system had issues with highly reflective surfaces, which is the typical model finish for ETW and NTF models. At low temperatures, the reliability of the system was not as satisfactory. This system also did not allow for roll angles, since the retro reflector would move way from the illumination beam.

IV. Emerging Parallel Technologies

Attitude measurement is not solely important to wind tunnel testing, in many other fields it is crucial to have precise angle measurements. There has been a recent boom in virtual or augmented reality systems that rely on low-latency and high accuracy head tracking. If these systems did not have low-latency or high accuracy, then users will feel more nauseous due to motion sickness. These systems have been creating novel solutions that are both “inside-out” and “outside-in”, such as onboard cameras or sensors versus external cameras tracking the target, respectively. Many of the solutions that virtual or augmented reality systems use are very similar to ones previously developed for wind-tunnel attitude measurement. For example “outside-in” such as Sony’s Playstation VR has stereo cameras track lit targets similar to Optotrak. HTC Vive is an example of an “inside-out” system where two “lighthouses” illuminate the system with sweeping lasers sheets. Photodiodes on the HTC Vive detect the laser sheet passes and compute the location and orientation of the system. This method of attitude measurement is similar to the laser yaw meter developed by the Royal Aircraft Establishment, as discussed in an earlier section.

V. Recommendations

As many have said before, there is no perfect attitude measurement system, but there are those that work well. Q-Flex accelerometers are the most widely used for there simplicity and accuracy, but are plagued with vibration issues. Most of these vibration issues can be mitigated with isolation pads, and stingwhip corrections. Continuous development of MEMS accelerometer sensors for applications such as smart phones, virtual reality headsets, and unmanned aerial vehicles makes them attractive to use in small models that can not accommodate Q-Flexs. MEMS accelerometers will still suffer from rectification errors and stingwhip, but is currently not researched well. Optical techniques provide a vibration free measurement, however falls victim to tunnel or support structure movement.

From this, it is suggested that not only one type of sensor is studied and implemented for all facilities, but a spectrum of solutions is required. Wind-tunnel models can be separated into three different size groups for subsonic/transonic, supersonic, and hypervelocity. With increases in speed the model sizes generally decrease, which requires different measurement techniques for each. Subsonic and transonic facilities where models are large enough to accommodate should continue to use Q-Flex sensors and research vibration issues if necessary for accuracy. MEMS type sensors, should be strongly considered for smaller supersonic facilities with further research into possible vibration issues and stingwhip. Hypervelocity facilities will require the use of off-body techniques due to the lack of model space, for most facilities, where photogrammetry methods show promise. New techniques should be developed so that photogrammetry techniques can account for movement of the tunnel walls or camera support structure.

References

[1] Steinle, F. and Stanewsky, E., “Wind Tunnel Flow Quality and Data Accuracy Requirements,” Tech. Rep. AGARD Advisory Report No. 184, AGARD, Nov. 1982.

[2] McDevitt, T. K. and Owen, F. K., “An optical angle of attack sensor,” *IEEE Aerospace and Electronic Systems Magazine*, Vol. 5, No. 2, 1990, pp. 19–27.

[3] Wong, D. T., “Evaluation of electrolytic tilt sensors for wind tunnel model angle-of-attack measurements,” NASA Langley Research Center, Hampton, VA 23681-2199, United States, 1991, pp. 382–391, cited By 2.

[4] Wong, D. T., “Evaluation of electrolytic tilt sensors for measuring model angle of attack in wind tunnel tests,” Tech. Rep. TM-4315, NASA Langley Research Center, NASA Langley Research Center, Hampton, VA 23681-2199, United States, Feb. 1992.

[5] Wong, D. T., “Evaluation of the prototype dual-axis wall attitude measurement sensor,” Tech. Rep. TM-109056, NASA Langley Research Center, NASA Langley Research Center, Hampton, VA 23681-2199, United States, Feb. 1994.

[6] Finley, T. and Tcheng, P., “Model attitude measurements at NASA Langley Research Center,” American Institute of Aeronautics and Astronautics, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 1992.

[7] Crawford, B. L., “Angle Measurement System (AMS) for Establishing Model Pitch and Roll Zero, and Performing Single Axis Angle Comparisons,” Vol. 20, American Institute of Aeronautics and Astronautics, Aeronautics Systems Engineering Branch, NASA Langley Research Center, Hampton, VA 23681, United States, 2007, pp. 13930–13939.

[8] Tripp, J. S., Wong, D. T., Finley, T. D., and Tcheng, P., “Improved calibration technique for wind tunnel model attitude sensors,” NASA Langley Research Center, Hampton, VA 23681-2199, United States, 1993, pp. 89–97.

[9] Marshall, R. and Landman, D., “An improved method for determining pitch and roll angles using accelerometers,” Department of Aerospace Engineering, Old Dominion University, Norfolk, VA 23529, United States, 2000.

[10] Strganac, T. W., "A Study of the Aeroelastic Stability for the Model Support System of the National Transonic Facility," No. AIAA 88-2033, 1988.

[11] Whitlow, Woodrow, J., Bennett, R. M., and Strganac, T. W., "Analysis of vibrations of the National Transonic Facility model support system using a 3-D aeroelastic code," American Institute of Aeronautics and Astronautics, NASA Ames Research Center; Moffett Field, CA, United States, 1989.

[12] Young, C. P., Popernack, T. G., and Gloss, B. B., "National transonic facility model and model support vibration problems," *National Transonic Facility Model and Model Support Vibration Problems*, 1990.

[13] Buehrle, R. D., Young Jr., C. P., Balakrishna, S., and Kilgore, W. A., "Experimental study of dynamic interaction between model support structure and a high speed research model in the national transonic facility," *Experimental Study of Dynamic Interaction between Model Support Structure and a High Speed Research Model in the National Transonic Facility*, 1994.

[14] Young, C. J. P., Buehrle, R. D., Balakrishna, S., and Kilgore, W. A., "Effects of vibration on inertial wind-tunnel model attitude measurement devices," Tech. Rep. 109083, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 1994.

[15] Buehrle, R. D., "Dynamic response tests of inertial and optical wind-tunnel model attitude measurement devices," *NASA Technical Memorandum 109182*, Feb. 1995.

[16] Crawford, B. and Finley, T., "Improved correction system for vibration sensitive inertial angle of attack measurement devices," American Institute of Aeronautics and Astronautics, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 2000.

[17] Crawford, B. L. and Finley, T. D., "Results from a Sting-Whip-Correction Verification Test in the Langley 16-Foot Transonic Tunnel," 2002.

[18] Kahng, S. K., Hernandez, C. D., Gorton, S. A., Adcock, E. E., Jordan, T., Culliton, W. G., Lawrence, R. M., and Soto, H. L., "MEMS sensor system development at NASA Langley Research Center for wind tunnel applications," American Institute of Aeronautics and Astronautics, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 2002.

[19] Newman, B. and Yu, S., "Development of a high accuracy angular measurement system for langley research center hypersonic wind tunnel facilities," *Development of a High Accuracy Angular Measurement System for Langley Research Center Hypersonic Wind Tunnel Facilities*, 2002.

[20] Yu, S. and Newman, B., "Development of a High Accuracy MEMS Angular Measurement System for Hypersonic Wind Tunnel Facilities," American Institute of Aeronautics and Astronautics, Department of Aerospace Engineering, Old Dominion University, Norfolk, VA 23529, United States, 2003.

[21] Crawford, B. L. and Rhode, M. N., "Miniature on-board angle of attack measurement system for hypersonic facilities," Vol. 1, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 2006, pp. 233–243.

[22] CHRUSCIEL, G., "Three degree of freedom hypersonic wind tunnel results employing onboard rate gyros. I - Asymmetric body," American Institute of Aeronautics and Astronautics, Lockheed Missiles & Space Company, Inc., Sunny vale, CA, United States, 1976.

[23] CHRUSCIEL, G., "Three degree of freedom hypersonic wind tunnel results employing onboard rate gyros. II - Symmetric body," American Institute of Aeronautics and Astronautics, Lockheed Missiles & Space Company, Inc., Sunny vale, CA, United States, 1976.

[24] CHRUSCIEL, G. and FRENCH, N., "3 DOF gyro analysis from measured and derived rates," Aerospace Sciences Meetings, American Institute of Aeronautics and Astronautics, Lockheed Missiles & Space Company, Inc., Sunny vale, CA, United States, Jan. 1982.

[25] Stroezel, M., Saaro, J., Stieler, B., and Eckert, W., "Windtunnel Model Attitude Measurement with a Fiberoptic Gyro." 1995.

[26] Rueger, M., "The use of an inertial-gyro system for model attitude measurement in a blow-down wind tunnel," Vol. 2005, AIAA, United States, 2005, pp. 384–401.

[27] Rueger, M. and Lafferty, J., "Demonstration of a Gyro-Based Model Attitude Measurement System at the AEDC Tunnel 9 Test Facility," American Institute of Aeronautics and Astronautics, The Boeing Company, St. Louis, MO, 63166, United States, 2008.

[28] Fuijkschot, P. H., "Model incidence measurement using the SAAB Eloptopos system," *International Congress on Instrumentation in Aerospace Simulation Facilitie*, National Aerospace Laboratory NLR Amsterdam, the Netherlands, Sep 1989, pp. 125–128.

[29] Lamiscarre, B. B., Sidoruk, B., Selvaggini, R., Castan, E., and Bazin, M., "Stereo-optical system for high-accuracy and high-speed 3D shape reconstitution: wind-tunnel applications for model deformation measurements," Vol. 2273, ONERA CERT/DERO, Toulouse, France, 1994, pp. 46–55.

[30] Eitelberg, G. and Eckert, D., "Some developments in experimental techniques of the German-Dutch Wind Tunnels (DNW)," American Institute of Aeronautics and Astronautics, German-Dutch Wind Tunnels (DNW), Marknesse, The Netherlands, 2000.

[31] Jones, T. and Hoppe, J., "Comparison of angle of attack measurements for wind tunnel testing," American Institute of Aeronautics and Astronautics, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 2001.

[32] Lee, G., "Study of Optical Techniques for the Ames Unitary Wind Tunnels, Part 3. Angle of Attack Progress Report," Tech. Rep. CR-192165, NASA Ames Reserch Center, NASA Ames Reserch Center, Mountain View, CA, United States, Jan. 1993.

[33] Watzlavick, R. L., Crowder, J. P., and Wright, F. L., "Comparison of model attitude systems: Active target photogrammetry, precision accelerometer, and laser interferometer," Boeing Commercial Airplane Group, Aerodynamics Laboratory, Seattle, WA, United States, 1996.

[34] Burner, A., Radeztsky, R., and Liu, T., "Videometric applications in wind tunnels," Vol. 3174, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 1997, pp. 234–247, cited By 15.

[35] Snow, W. L., Childers, B. A., Jones, S. B., and Fremaux, C. M., “Recent experiences with implementing a video-based six-degree-of-freedom measurement system for airplane models in a 20-foot-diameter vertical spin tunnel,” Vol. 1820, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 1993, pp. 158–180.

[36] Ruyten, W., “Toward an integrated optical data system for wind tunnel testing,” American Institute of Aeronautics and Astronautics, Sverdrup Technology, Inc., AEDC Group Arnold Engineering Development Center Arnold Air Force Base, Tennesse, United States, 1999.

[37] Ruyten, W., “Model Attitude Determination in Wind Tunnel with a Luminescent Paint Data System,” *AIAA Journal*, Vol. 38, No. 9, 2000, pp. 1692–1697.

[38] Jones, T. and Lunsford, C., “Design and development of a real-time model attitude measurement system for hypersonic facilities,” NASA Langley Research Center, Hampton, VA 23681-2199, United States, 2005, pp. 5489–5498.

[39] Jones, T. W. and Lunsford, C. B., “A photogrammetric system for model attitude measurement in hypersonic wind tunnels,” Vol. 20, NASA Langley Research Center, Hampton, VA 23681-2199, United States, 2007, pp. 13952–13961.

[40] Ruyten, W., “Model attitude measurement with an eight-camera pressure-sensitive paint system,” Sverdrup Technology, Inc., AEDC Group Arnold Engineering Development Center Arnold Air Force Base, Tennesse, United States, 2000, cited By 4.

[41] Otter, D., Moller, T. J., and Butefisch, K. A., “An optical position monitoring system for investigation of model displacement and transient motion of wind tunnel models,” DLR, BunsenstraBe 10, 37073 GOttingen, Germany, 2001, pp. 140–143.

[42] Martinez, B., Bidino, D., Bastide, M., Demeautis, C., Leopold, F., and Wey, P., “Motion measurement of a wind tunnel model by stereovision technique,” American Institute of Aeronautics and Astronautics, French-German Institute of Research of Saint Louis (ISL), BP 70034, 68301 Saint Louis CEDEX, France, 2015.

[43] Liu, W., Ma, X., Li, X., Chen, L., Zhang, Y., Li, X., Shang, Z., and Jia, Z., “High-precision pose measurement method in wind tunnels based on laser-aided vision technology,” *Chinese Journal of Aeronautics*, Vol. 28, No. 4, 2015, pp. 1121–1130.

[44] Zeringue, K., “An optical method for model attitude measurements,” American Institute of Aeronautics and Astronautics, University of Tennessee, Space Institute, Tullahoma, TN, United States, 1977.

[45] Bomar, B. W., Goethert, W. H., Belz, R. A., and Bentley, III, H. T., “The Development of a Displacement Interferometer for Model Deflection Measurements,” No. ADA034384, Arnold Engineering Development Center (DYFS), Arnold Air Force Station, Tennessee 37389, United States, 1977.

[46] Crowder, J. P., Hill, E. G., and Pond, C. R., “Selected wind tunnel testing developments at the Boeing Aerodynamics Laboratory,” Aerodynamic Testing Conference, American Institute of Aeronautics and Astronautics, The Boeing Company, Seattle, WA, United States, March 1980.

[47] Pond, C. R. and Hill, E. G., “Laser Measurement of Angle of Attack on Wind-Tunnel Models,” *Astronautics & Aeronautics*, Vol. 19, No. 1, Jan. 1981, pp. 56–57, 59.

[48] Pond, C. R., Texeira, P. D., and Wilbert, R. E., “Laser angle measurement system,” Tech. Rep. CR-159306, United States, Oct. 1980.

[49] Pond, C. R. and Texeira, P. D., “Laser angle sensor development,” Tech. Rep. CR-159385, NASA, The Boeing Company, Seattle, WA, United States, Oct. 1980.

[50] Pond, C. R. and Texeira, P. D., “Laser Angle Sensor,” Tech. Rep. CR-172369, NASA, The Boeing Company, Seattle, WA, United States, Sept. 1985.

[51] Jeffery, R. W., Law, R. D., Tuck, A. N., and Hill, R. P., “A Description of the Model Attitude Measurement and Control System in Use in the 5 Metre Pressurised Low Speed Wind Tunnel,” *RAE Report in preparation*, 1980.

[52] Crites, R., “Development of a Simple Optical Pitch Sensor,” 1986.

[53] Owen, F., McDevitt, T., Morgan, D., and Owen, A., “Wind tunnel model angle of attack measurements using an optical model attitude system,” American Institute of Aeronautics and Astronautics, Cornplere Inc. Pacific Grove, CA, United States, 2000.

[54] Ansell, D. M. and Schimanski, D., “Non-intrusive optical measuring techniques operated in cryogenic test conditions at the European transonic windtunnel,” ETW GmbH, Ernst Mach Strasse, Kln, Germany, 1999.