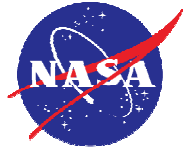


Technology Review and Road-Mapping of Wind-Tunnel Angle Measurement

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Force and Angle Connection

- All balance calibrations rely on a form of angle measurement
 - Releveling
 - Position monitoring
- Angle measurement during wind tunnel testing
 - Model position control
 - Rotation of body fixed axis to wind axis
- AGARD quotes: $\Delta C_D = 0.0001 \rightarrow \Delta \alpha = 0.01$

Angle Measurement Accuracy $\leftrightarrow$ Force measurement Accuracy

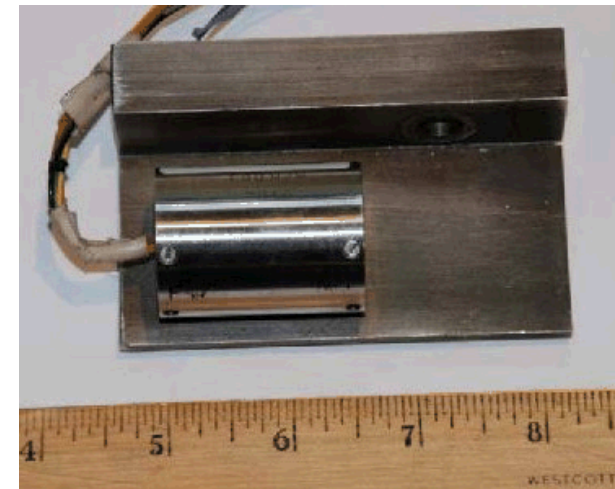
Inertial Based Sensors

Accelerometers – Q-Flex

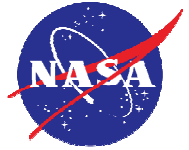
- **Most commonly used sensors at facilities**
 - Simple to use
 - High Repeatability
 - Relatively compact
- **Temperature Sensitive**
 - Corrected with internal RTD
- **Vibration induced errors**
 - Rectification error, overcome with isolation pads surrounding sensor
 - Stingwhip bias, can be corrected with additional instrumentation



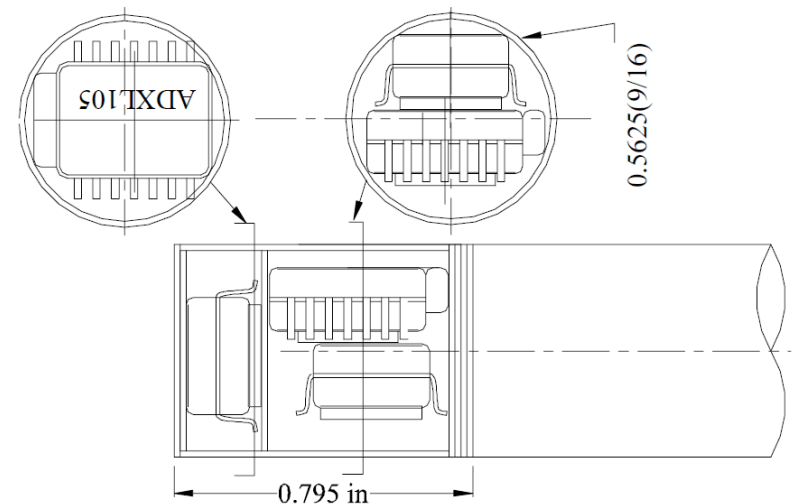
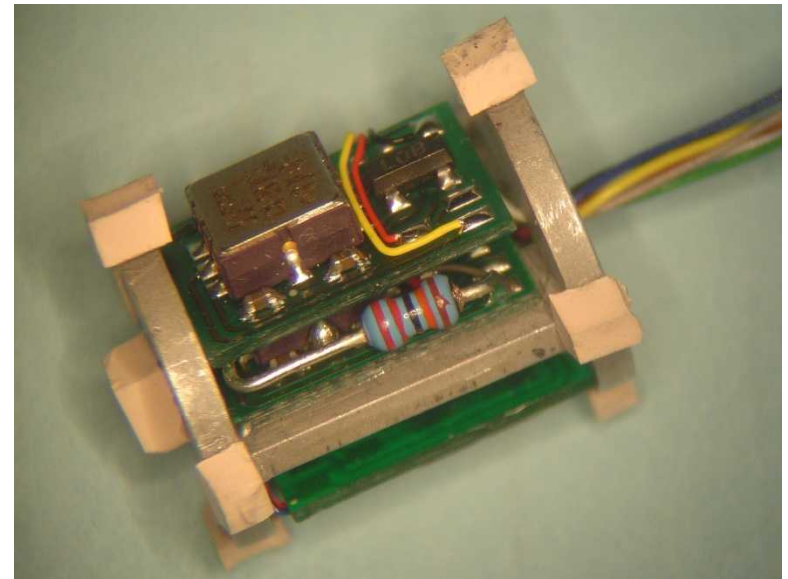
Credit: Honeywell



Accelerometers – MEMS



- Micro-electro-mechanical sensors are silicon based mini sensors
- Compact size, planform as small as a finger nail
- Lower sensitivities and higher noise than Q-Flex sensors
- Testing by Crawford shown accuracies of 0.009° for a $\pm 24^\circ$ angle range
- Similar vibration issues as Q-Flex accelerometers



Gyroscopes Overview

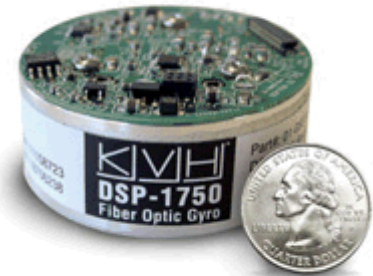


- **Measures angular rate instead of angle**
 - Requires single integration to resolve angles
 - Can measure rates in multiple directions (Pitch, Roll Yaw)
- **Typically have drift, or random walk, issues**
 - Mitigated by several analytical methods
 - DLR utilized common force measurements to correlate angle estimates, for example 100 lb normal force = 2°
 - Boeing utilized secondary sensors to measure pre- and post-test wind off zeros to correct for drift
- **Do not rely on gravity vector, can be used in tunnels that feature floor balances**
- **Free of vibration issues of accelerometers**

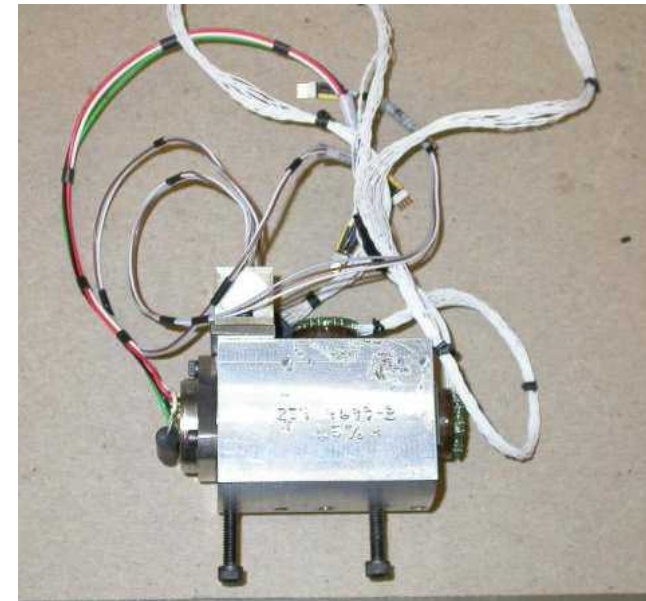
Gyroscopes – Types



- **Fiber optic gyroscope (FOG)**
 - Expensive (\$4000 Single Axis)
 - Larger than Q-Flex (1.8" Diameter DSP-1750)
- **Dynamically tuned gyroscope (DTG)**
 - Measures torque on a rotating rotor
 - Similar size to Q-Flex sensors
 - Testing by Boeing showed total uncertainty of 0.05-0.1°
- **MEMS**
 - Very compact
 - Newman and Yu observed erratic drifts
 - Could not support a measurement capability of $\pm 0.1^\circ$



Credit: KVH



Optical Techniques

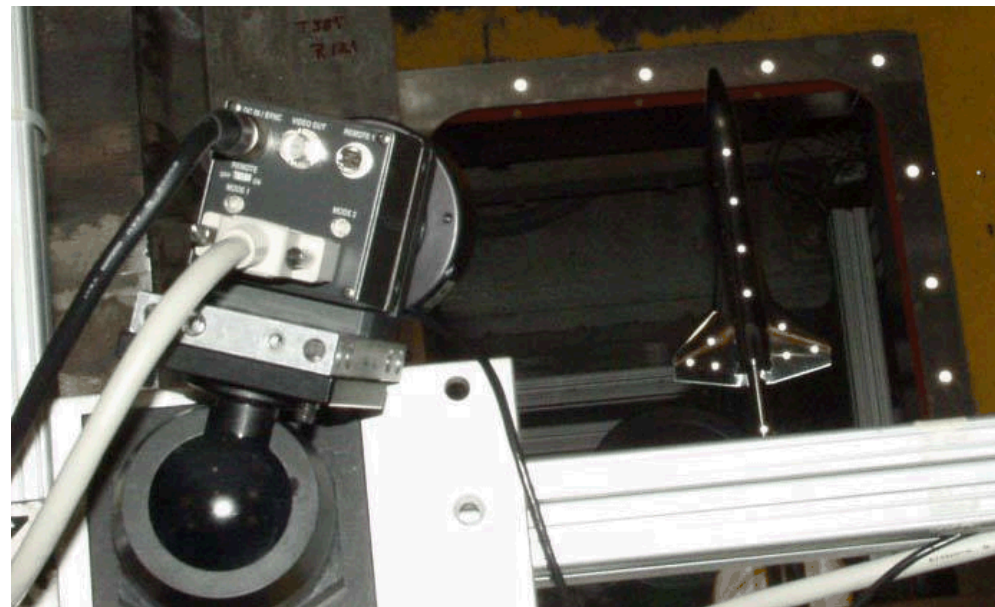
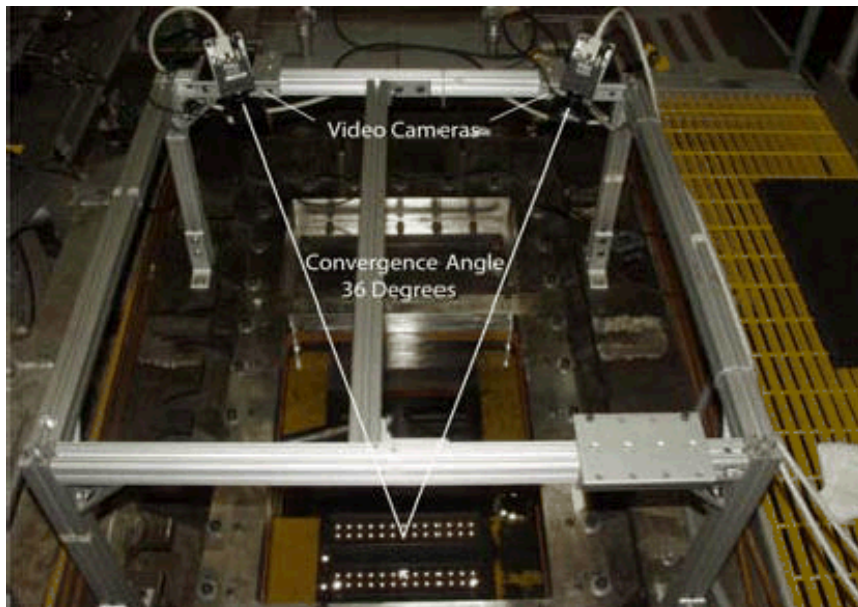
Optical Techniques Overview



- **Independent of model vibrations**
- **Removes sensors from the model**
 - **Secondary angle sensor is required for calibration and checks**
- **Can resolve all 6-degrees of freedom (x, y, z, pitch, roll, yaw)**
- **Calibration is model dependent, requiring calibrations for every entry and possible model changes**
- **Observed that camera support and tunnel wall movement can affect overall system performance**

Photogrammetry – Reflective Targets

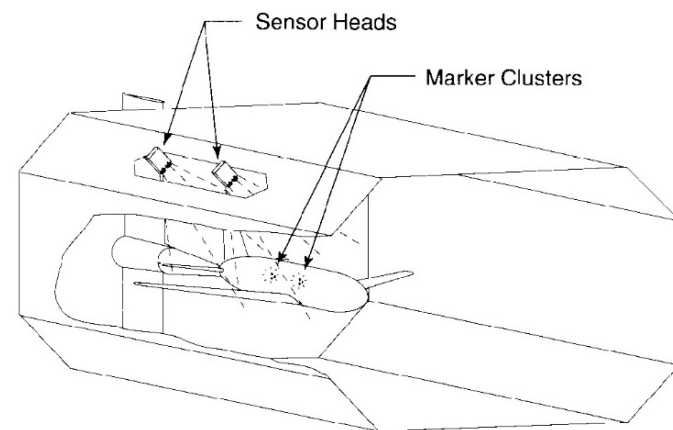
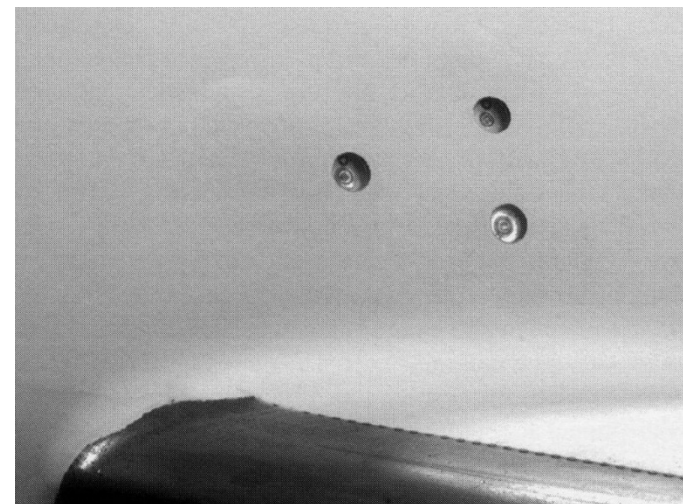
- Requires multiple camera access, ideal 60° to 90° convergence angle
- Reflective targets preclude onboard electronics for angle measurement
- LaRC 31-Mach: $\pm 0.057^\circ$ (95% prediction interval) for pitch.
- AEDC: $\pm 0.06^\circ$ discrepancy from traditional measurements



Photogrammetry – Self-illuminating Targets

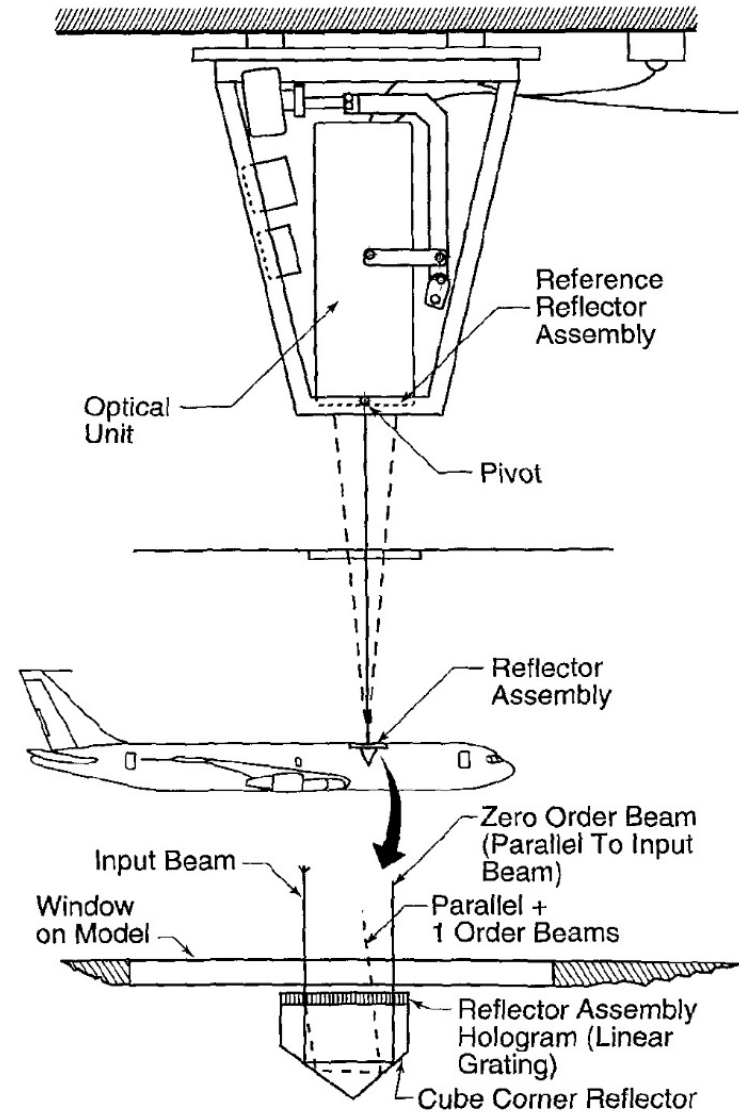


- Self-illuminating targets helps prevent issues with glare and other light issues
- Typically infrared targets flash at different times to map the target locations
- Multiple systems have been developed:
 - ELOPTOPS by SAAB
 - Optotrak
 - Tested at LaRC 14x22, LaRC TDT, Boeing TWT
 - RADAC by CERT
- Can provide accuracies of $\pm 0.0035^\circ$



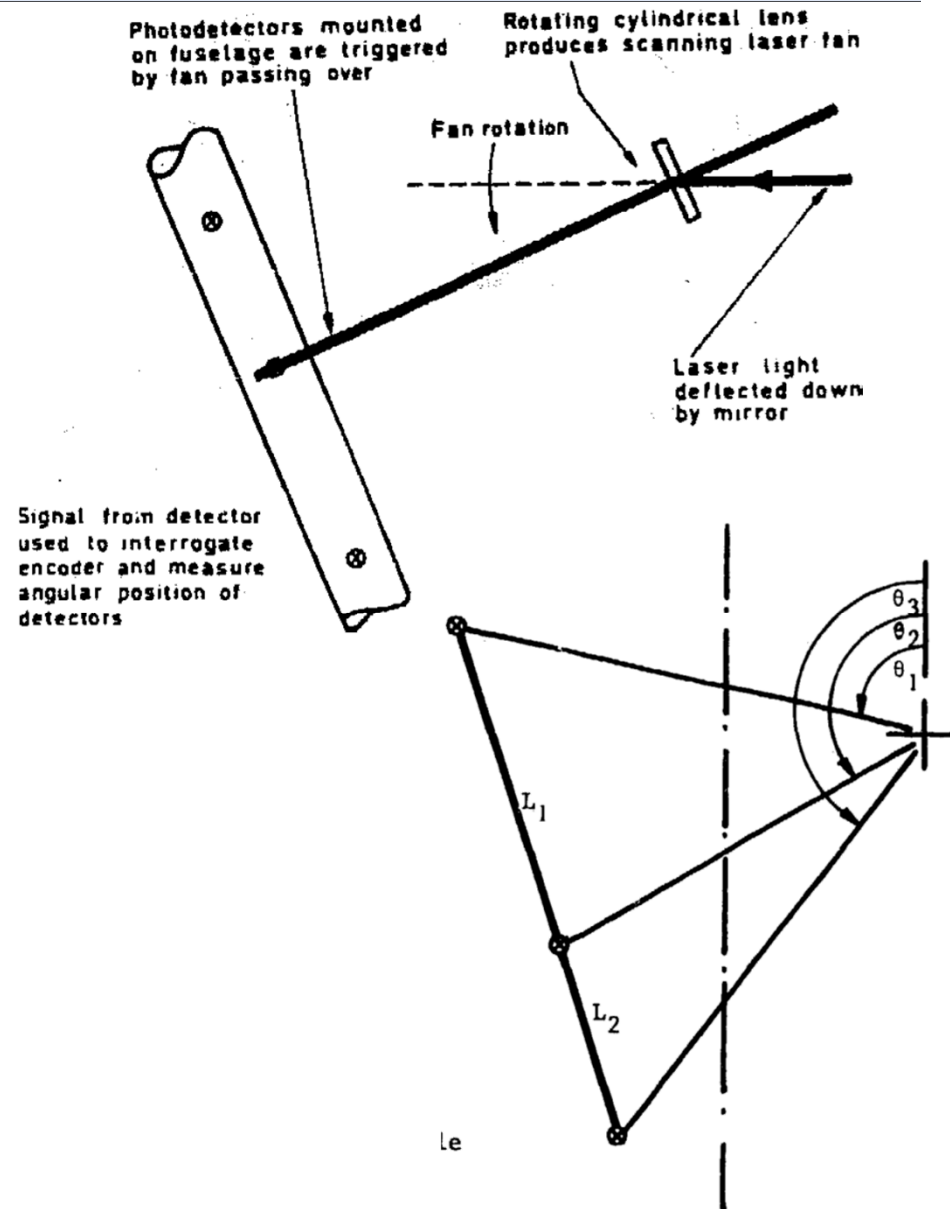
Laser Systems – Boeing Laser Angle Meter

- Developed from 70's-90's, systems built for:
 - Boeing TWT
 - LaRC NTF, 0.3m TCT, 8-Ft TPT
 - Ames 14-Ft, 11x11 TWT
- Based on laser interferometry
 - Counts fringes as model moves or pitches
- Pitch only systems developed, roll was investigated
- Root means square error of 0.002°



Laser Systems – Laser Angle Meter

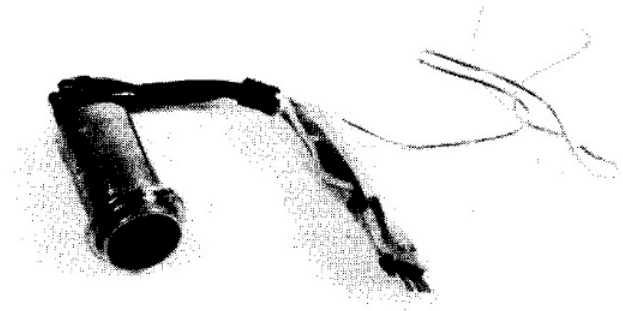
- Developed by Royal Aircraft Establishment in 1970s
- Based on a sweeping laser sheet illuminating photodiodes
- Yaw angle is determined by angles to the photodiodes and known target distances
- Quoted accuracy of $\pm 0.1^\circ$



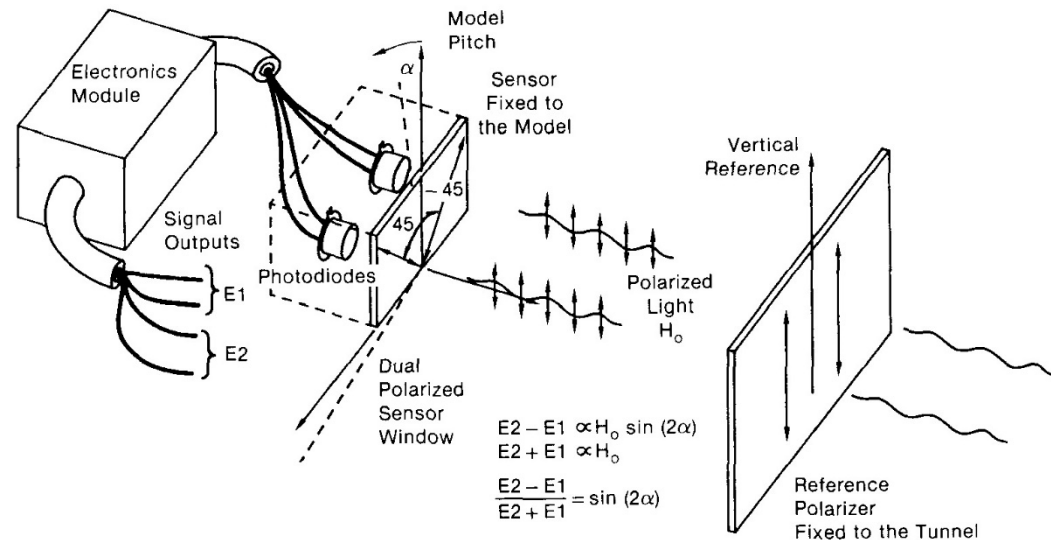
Other Optical Techniques – IMAP



- McDonnell Aircraft Co. infrared model angle position sensor (IMAP)
- Implemented polarized light and sensors with polarized filters to measure light intensity changes with angle
 - Requires tunnel access for lamp

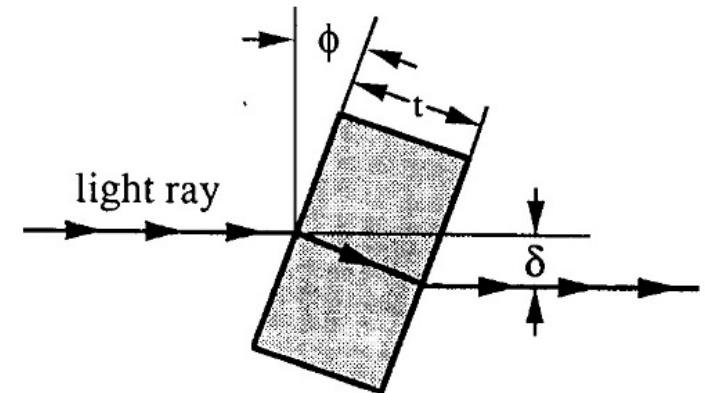


- 95% confidence interval of 0.04°

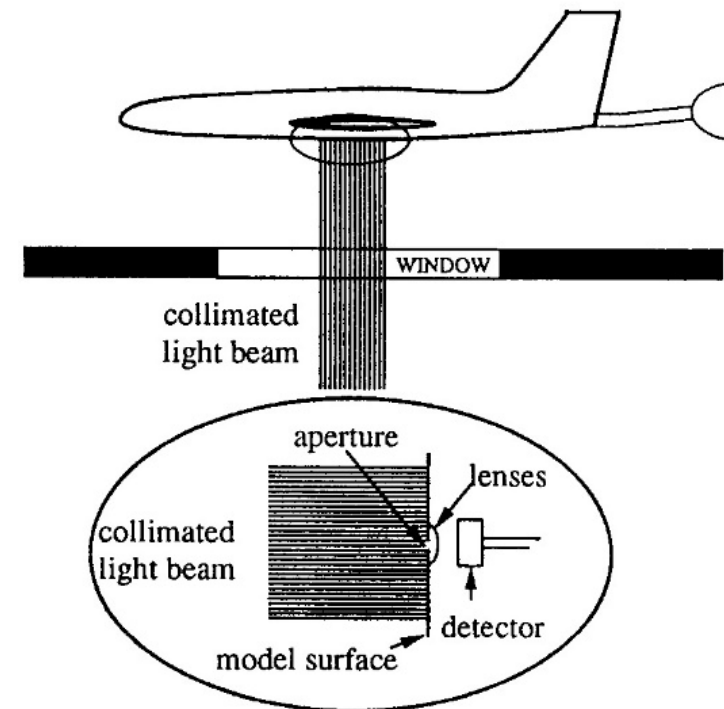


Other Optical Techniques – Optical Angle Sensor

- Developed by Complere Inc. in the 1990s
 - Tested at Ames 14-Ft and 9x7-Ft
- Used the refraction of collimated light to displace tight light ray onto a photodiode array
 - Light displacement a function of sensor angle
- Quoted accuracies of 0.01° , and 0.03° for sensor ranges of $\pm 10^\circ$ and $\pm 20^\circ$



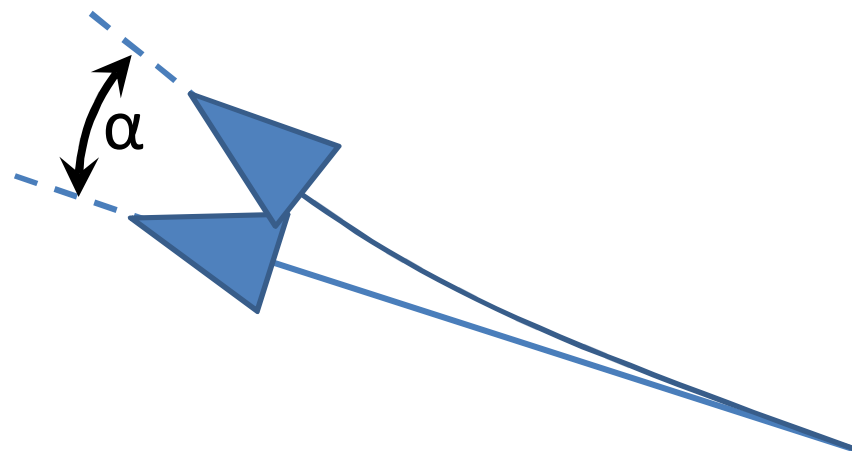
$$\delta = f(t, \phi, n)$$



Sting Deflections



- Utilizes an internal force balance to determine sting deflection angle
- Typically used when on-board is not possible due to model size
- Deflection model is generated during check load process
 - Sufficient points are required to develop proper model



Emerging Parallel Technologies



- **Recent evolution of virtual/augmented reality headsets**
 - Multiple solutions of head position and angle tracking
 - HTC VIVE utilizes similar technology to the laser yaw meter
- **Jet fighter helmet heads up displays**
 - Similar solutions to virtual/augmented reality
 - Robust solutions to harsh loads and electrical noise
- **Growth of UAVs**
 - Pushing development of MEMS based solutions
 - Decreased cost in accelerometers, gyroscopes

Summary



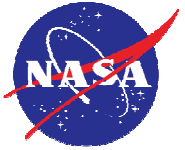
- **Collection of techniques are required**
 - **Accommodate spectrum of model sizes**
- **Leverage techniques developed for other parallel technologies areas**
 - **Virtual/augmented reality techniques**
 - **Development of UAV measurement solutions**
- **Enhance current capability**
 - **Ensure technique problem areas are resolved**
 - **Determine current measurement capability and add to areas lacking accuracies desired by the researcher**

11th Balance Symposium Angle Panel Summary

Balance Symposium Panel Members



- **Ray Rhew (Moderator) – Langley D201**
- **Anton Gorbushin**
 - Head of Laboratory, Aerodynamic Department
 - Central Aerohydrodynamic Institute (TsAGI, Russia),
- **Martin Wright**
 - Manager Aerodynamics & Testing
 - European Transonic Windtunnel (ETW), Cologne Germany
- **Henry Bennett**
 - Aero/Noise/Propulsion Laboratory
 - Boeing Company, Seattle, Washington
- **Ken Toro, NASA Langley Research Center**
- **Xiang Guangwei**
 - China Aerodynamics Research and Development Center (CARDIC), Mianyang, China



- **Q-Flex sensors are placed in heated enclosures**
 - **Use three-axis accelerometers is model nose is large enough**
 - **Temperature compensated**
 - **Calibration is not conducted on the Q-Flex, but misalignments are measured by level checks**
 - **Sting deflections are used to corroborate arc-sector Q-Flex with the onboard Q-Flex**
 - **Similar setup to what is currently utilized at NTF**
- **Half model testing uses table resolver**
- **Optical Angle Measurement System is used mostly for model deformation**
 - **Accuracy of 0.1 degree was stated**
- **MEMS based solutions were studied by were not found to be sufficient for 0.01 degree accuracies**
- **Side conversations revealed a potential need for smaller packages (unique model)**

CARDC Summary



- One main remark was the exclusion of sting deflection based angle measurements
 - Stated uncertainty of 0.015°
- CARDC does use accelerometer and camera systems for angle measurement
- A Videogrammetry system is implemented at CARDC's 2 meter supersonic wind tunnel
 - Standard deviation ranging from 0.0018 to 0.0094 degree, and uncertainty of 0.003 degree

TsAGI Summary



- Primary go to is an accelerometer built in Russia
 - TsAGI is actively involved with the development of further sensors
 - Dynamics response seemed important, **increasing natural frequency** accelerometers to 3kHz from 2kHz
 - Temperature compensated
- MEMS sensors are used in smaller models
- Half models use optical encoders
- Interest in model position measurement and instantaneous angle measurement

Boeing Summary



- Top remark was that Boeing lost technology through loss of personnel, and went down a path to **reduce complexity**
- AoA accuracies depend on tunnel testing (both 1 drag count)
 - 0.01 Commercial Airplanes
 - 0.05 for Defense and Space
- Q-Flex (QA-2000) accelerometers are used
- Photogrammetry is used “infrequently” with accuracies “better than 0.01” for both alpha and beta
- Future outlooks:
 - Attitude measurement tech in UAVs
 - Fiber Optic Gyroscopes

Panel Discussion Summary



- A general theme was the need for **simplicity** of use and evidenced by the minimal use of optical techniques even though some showed very good capabilities.
- Balance and system deflections were stated as a method that is used quite often to satisfactory results based on the application needs. Most mentioned linear math models to estimate.
- There was general agreement that a future session at the balance symposium is warranted.
- A survey will be developed and distributed to organizations to help baseline the technology.

Final Statements



- **Most facilities have optimize towards depending on Q-Flex accelerometers**
 - **Have been proven accuracy, drift and repeatability**
 - **Simple to use with minimal setup**
- **Most facilities have not produced any revolutionary sensors**
 - **Only active work seems to be TsAGI increasing frequency response of the sensor**
- **Miniaturization seems to be an important goal for some facilities**
- **Gyroscope or inertial measurement units (IMUs) seem to be promising with increasing development of UAV and AR/VR technology**

Current Work

Future Outlook



- **Engage with other wind-tunnel facilities to share current techniques**
- **Procure new sensors for test and validation**
 - **Accelerometer used by TsAGI**
- **Document current facility practices and identify challenges and gaps**
 - **Example, are model dynamics an issue that needs to be looked at**
- **An angle measurement group similar to the NFMTC would help facilitate discussions of current techniques and challenges**

Current Work – Angle Measurement Interns



- **Off-the-shelf MEMs sensors study**
 - Tested three (3) different sensors
 - Determined stability and repeatability
 - Designed miniature housing
- **Dynamic Environment Study – Rotorcraft Blade Measurement**
 - High sustained off-axis acceleration loading
 - High dynamic range – 650 degrees per second
 - Noisy environment – large electric drive (400 HP)



- **Develop a strategy for soliciting researchers' angle measurement demands and facility instrumentation requests from AETC facilities**
- **Align those demands with ARMD strategic thrusts and HEOMD development.**
- **Focus is on wind-on angle measurements**
 - **Not instrumentation/technique solutions or laboratory calibration**
- **These demands can include new, enabling capabilities where measurements are currently not available and enhancements to existing measurements.**