Aerodynamics and Performance Flight Research and Airworthiness Best Practices

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Introduction

- This presentation has been adapted from a talk given at AIAA Aviation in 2017
- Intent is to capture a wide variety of lessons learned and best practices in the area of flight research/test aerodynamics and performance
- A variety of AFRC researchers have contributed to the content in this presentation, including: Mike Frederick, Mark Davis, Trong Bui, Mark Smith, and Dan Banks
- About Me:
  - Approximately 20 years of experience in flight research and test at NASA
  - Aerodynamics lead on various projects including:
    - F/A-18 Active Aeroelastic Wing (AAW or X-53)
    - F-15B Quiet Spike
    - 747SP Stratospheric Observatory for Infrared Astronomy (SOFIA)
    - GIII Adaptive Compliant Trailing Edge (ACTE)
  - Chief of the Aerodynamics and Propulsion branch at NASA AFRC for 7 years
  - Currently the Assistant Branch Head for the Aerothermodynamics Branch at NASA LaRC

Preflight Analysis

- Required preflight analysis in the areas of aerodynamics and performance can vary dramatically from one flight project to another
  - Multiple wind tunnel entries across a broad flight regime with CFD analysis to augment
  - CFD analysis only
  - Quick analytical or empirical estimates
- The mission of the aircraft along with the planned flight envelope should be considered when identifying which preflight analyses should be performed
- Some things to consider for modifications to existing aircraft:
  - Quality of existing dataset that characterizes the baseline vehicle
  - Impacts to existing air data system and other related systems
  - Impacts to vehicle stability and control authority
  - Impacts to buffet boundary and stall speed
- Some things to consider for new aircraft:
  - Similarity to existing aircraft and applicability of existing analysis tools
  - Amount of legacy vs new systems in the aircraft
  - Identification of which systems are integrated as research systems

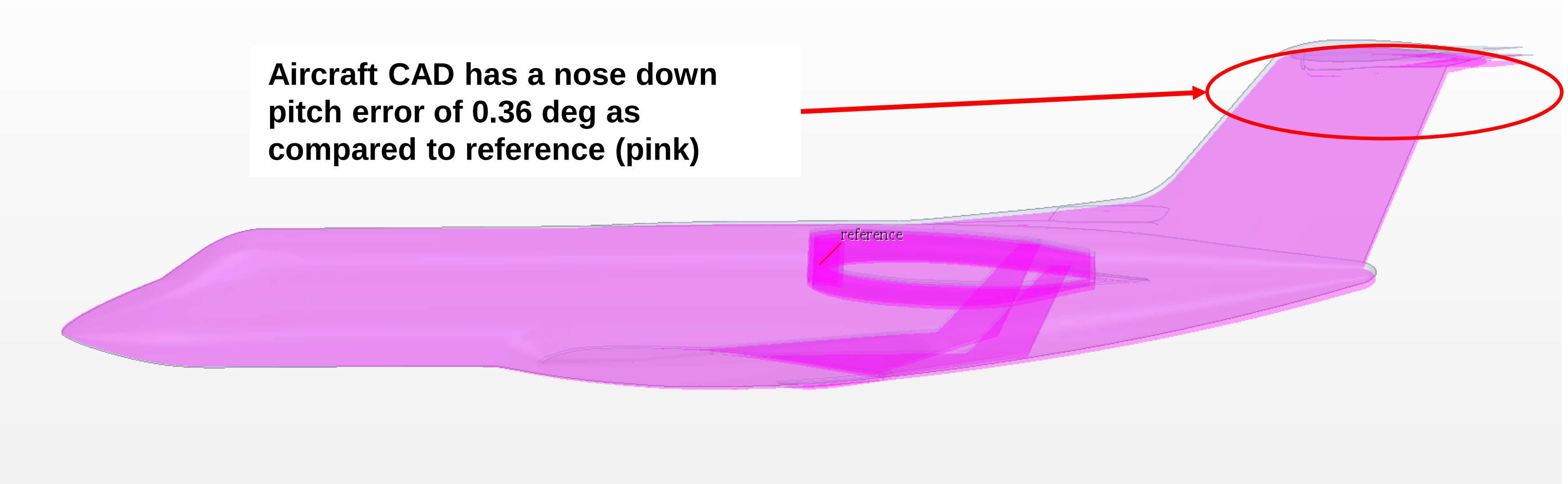
Aerodynamic Modeling

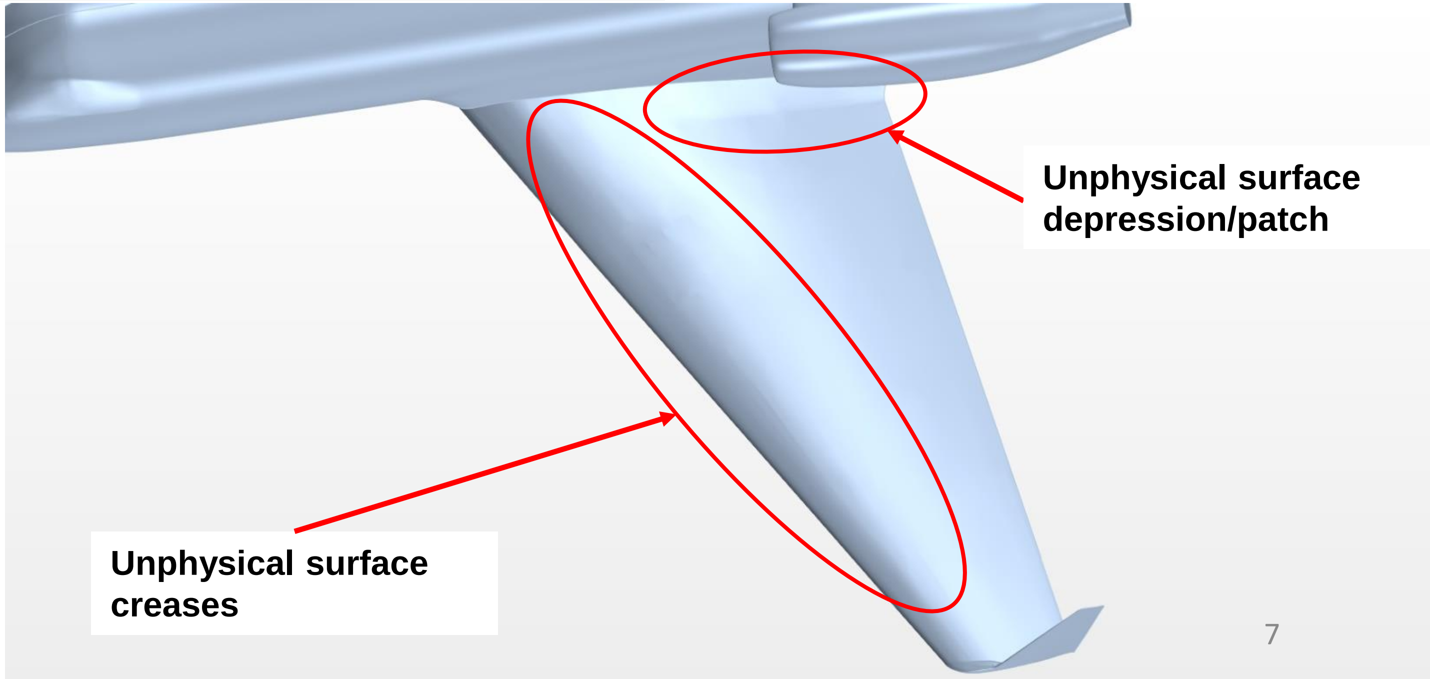
- Create an aerodynamic model with uncertainties for integration into a flight simulation
  - Comment the code and document the model, including appropriate use and limitations
  - Make note of the model's system of axes (body, stability, etc.)
  - Use version control
- Aerodynamic models can be created using wind tunnel data, CFD analysis, flight data or a combination of all three
  - Understand and document the strengths and weaknesses of the sources for the data
  - Using different tools and techniques to create data for the model adds value
  - Be aware of potential different conventions for flow angles, reference lengths, etc. when compiling data for the model
  - Stage data generation so that the aerodynamic model can be refined over time
- Plan to validate aerodynamic models and uncertainties with flight data during envelope expansion

Computational Fluid Dynamics

- Establish known and consistent aircraft reference coordinate system and origin as well as sign conventions for forces and moments, aircraft angles, and control surfaces
- Validate any new CFD codes/tools extensively
  - Simple validation test cases can be very effective in identifying bugs in codes
  - Compare validation results obtained from several different codes and CFD engineers
- Perform grid independence studies on the most complicated geometries and challenging flow physics to quantify CFD solution grid independence
  - Pay attention to both the global mesh as well as any locally complex regions and geometry features
  - Make sure that the grid refinements adequately address global and local complex flow/geometry features
- Consider using multiple CFD codes, particularly for challenging geometries or flow conditions, to provide additional confidence in the results and understanding of uncertainties
- Archive
  - All of the airplane CAD models, CFD simulation grids, solver inputs/settings, user scripts, and solutions that were used in airworthiness reviews
  - CFD codes and versions that have been used in support of airworthiness reviews
- CFD engineers should continue to interface with the project throughout the project lifecycle
- Check the aircraft CAD models against actual aircraft pictures and/or measurements of the as-built aircraft prior to using them in CFD work

Computational Fluid Dynamics





Flight Simulation

- Piloted and batch simulations are critical tools for flight research and test
- Flight simulations should use version control as part of a configuration control process
- Use piloted and batch simulation to help design and practice flight-test maneuvers, select test conditions, etc.
- Pilots practicing maneuvers, especially unique maneuvers, in the simulation prior to flight substantially improves flight test efficiency and quality of data from flight
- Flying maneuvers in the simulation after flights can also assist in fine-tuning aerodynamic parameters

Aerodynamics Instrumentation

- Start with project and research objectives and requirements
  - Plan for entire flight program
  - Consider the length of the total flight program for reliability and maintainability
- Instrumentation design should start early
  - Sensor requirements can affect airplane design parameters
  - Procurement time for some sensors can be longer than expected
- Request additional margin for your system
  - Modifying a system during a flight campaign is easier than making additions
- Understand the strengths and weakness of your selected sensors
- Calibrate and size sensors to be used for airworthiness for the full flight envelope and the worst-case environment for that sensor location
- Sensor/system owners should understand installation and calibration processes and be present during the actual work
- Thoroughly check and double check instrumentation locations, labels, and calibrations prior to the start of the flight campaign
- Good configuration control is essential
- Invest in processes and tools that make it easier to perform measurements and calibrations

Air Data

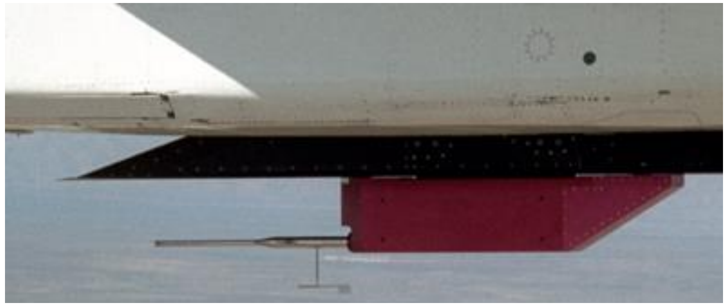
- Many options for research air data systems exist, including nose booms, FADS (Flush Air Data Sensing), production systems, and a variety of custom installations

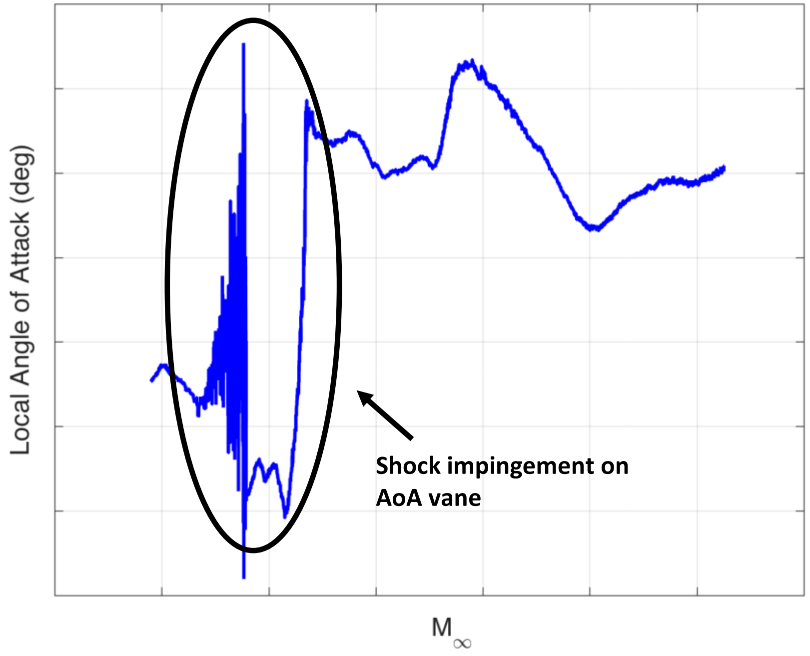
Air Data

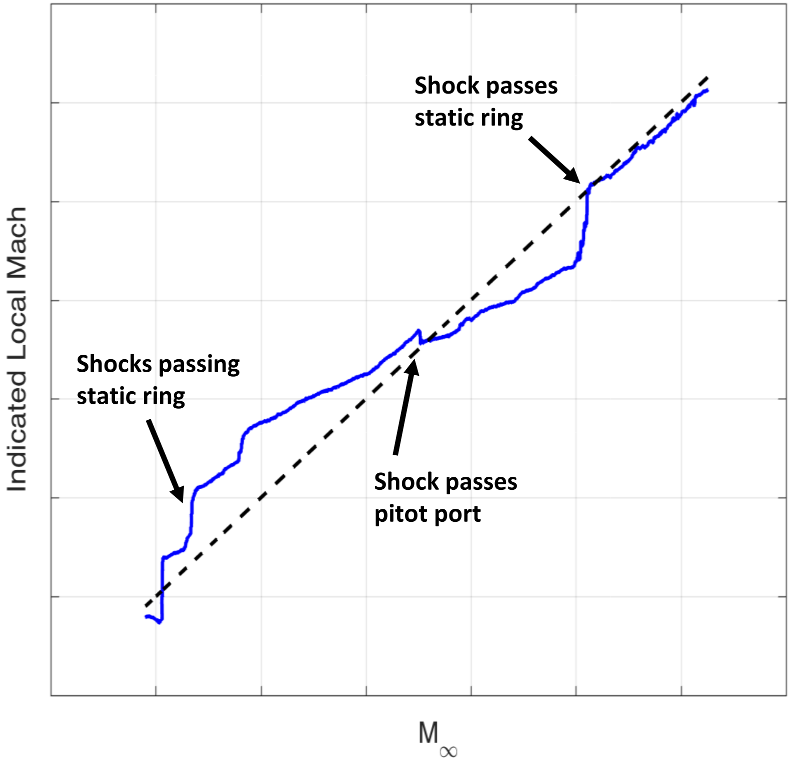
- Plan for in-flight air data calibration/validation
- Understand your air data measurement accuracy requirements prior to system design
- Know the strength and weaknesses of your air data system
  - FADS systems don’t affect airflow but require extensive calibration
  - NACA boom provides excellent results when mounted on the nose, but can be unreliable when used in flow fields with large spatial gradients because of the large separation distances between pitot and static ports, and flow vanes
  - Production air data systems often need additional calibration from flight data to achieve research-quality accuracy
  - Custom air data installations may not meet desired accuracies, even with extensive calibration

Air Data

NACA boom on CLIP under F-15B



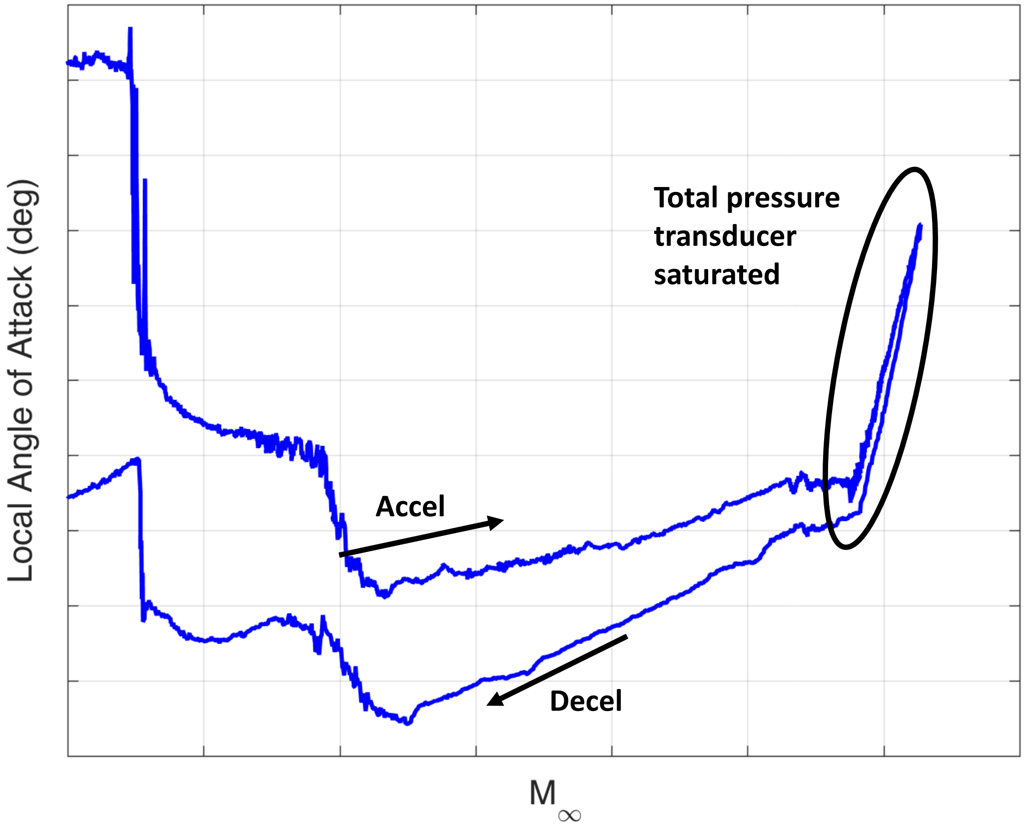




Aerodynamic Research Sensors

- Understand the strengths and weakness of your instrumentation system and selected aerodynamic sensors
  - Be aware of potential sensor effects on the phenomena you're measuring
  - Be wary of temperature effects on instrumentation
    - Temperature effects can sometimes mimic real phenomena occasionally leading to misinterpretation of data.
    - Temperature sensitivity of some types of instrumentation (e.g. piezoresistive pressure transducers) requires that the sensor be heated to a constant temperature due to the dynamic temperature ranges that can be experienced during flight test
  - Pneumatic effects (lag, attenuation, distortion) from tubing can adversely affect your measurements
- Understand your instrumentation measurement range, accuracy, and resolutions requirements
  - Relatively small errors in pressure measurement for an experimental wedge probe led to intolerable errors in the computed local air data. A subsequent sensitivity analysis after the first flight phase showed that relatively small errors in pressure (on the order of 1%) could give errors in angle of attack of up to 80%.

Aerodynamics Research Sensors



Flight Test

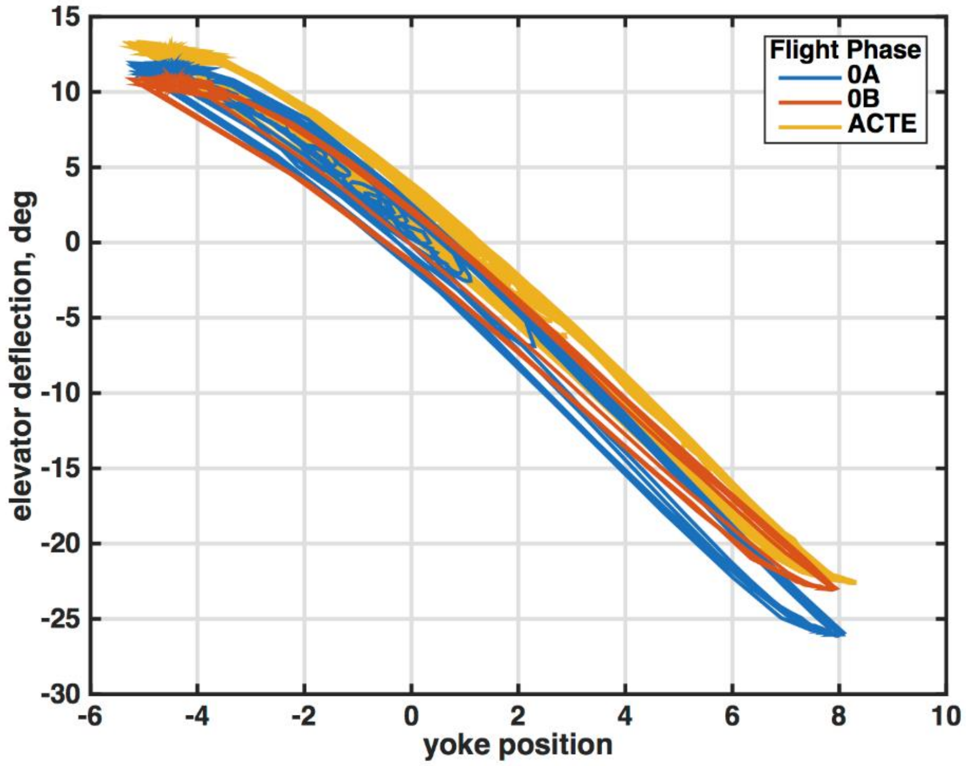
- Plan for the right pilot mix
  - Pilots all have different ways of doing things and having a good mix usually results in everyone learning more
  - Too many pilots can result in each pilot not having enough time to master the machine or maneuvers
- Have a well thought out bail-out plan for envelope expansion, especially at edges and corners of envelope
- Identify cliffs in CFD or wind tunnel data sets and look for them in-flight
  - Cliffs may not be where predicted but if they show up in CFD or wind tunnel data sets they may be out there
- Doing something, especially something unorthodox, on the fly without prior discussion and planning, will frequently surprise you with unexpected results
- Best practices for flight test techniques and maneuver design can vary notably from aircraft to aircraft
- Even two of the same airplane may behave differently in some situations
- Airplanes grow roots and test teams rust
  - An airplane that sits for a long time usually becomes more difficult to get flying again
  - A test team that has been out of the game/control room for a while, or has not worked together, will take some time to get up to speed
- Document and review
  - Discrepancies, flight test results, etc.
- Use your flight simulation

Flight Data Analysis

- Scrutinize your flight data early and often
- Instrumentation can change whenever an aircraft has been down for a while, even if it officially hasn’t changed
  - Recheck time shifts
  - Recheck control surface measurements’ calibrations
- Invest in analysis tools prior to the start of flight testing
- Be familiar with your analysis tools and scrutinize results carefully
- Actively compare predictions with analyzed flight data
- Understand how your flight data server modifies data for output
- Careful analysis of early results can allow for effective analysis automation later

Flight Data Analysis

Differences in surface position measurement between flight phases

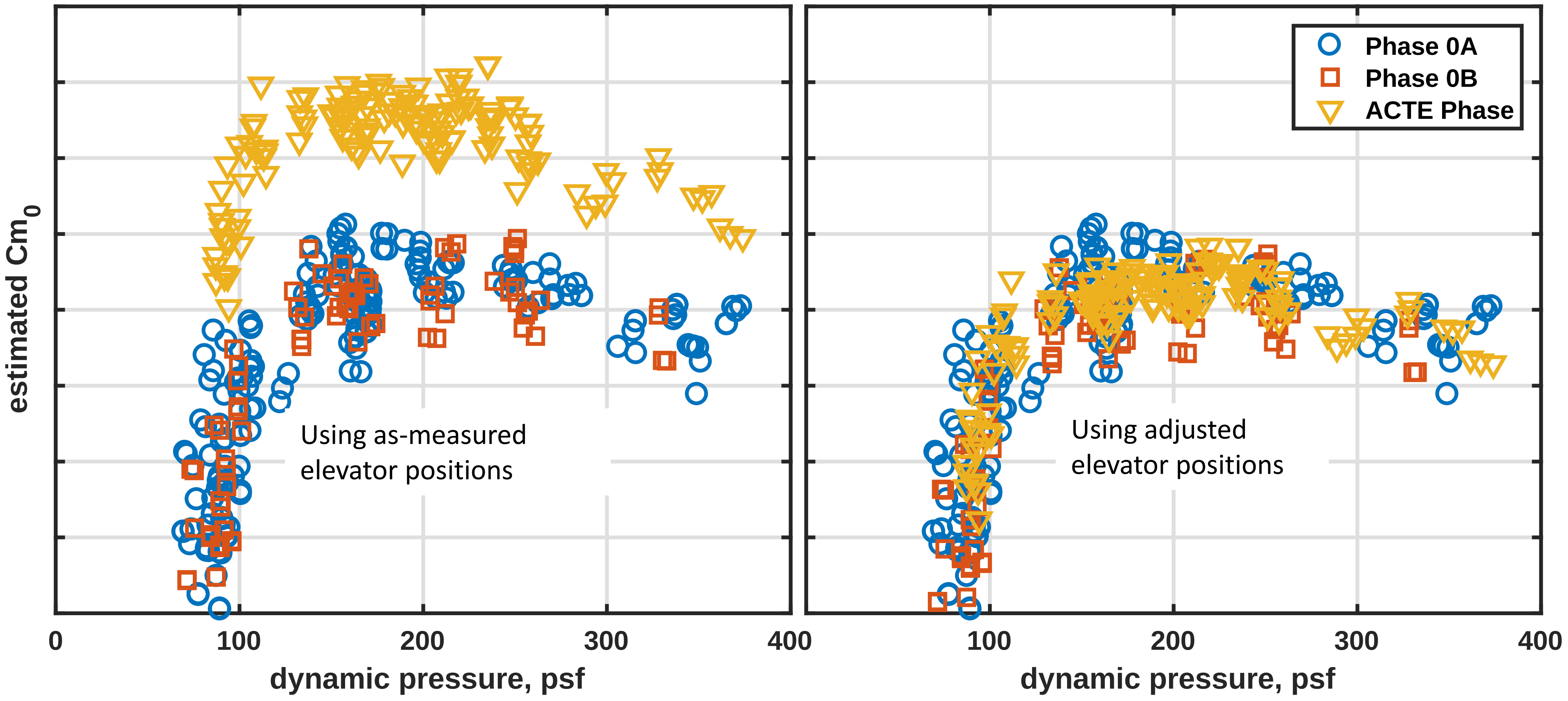


Differences in elevator deflection measurement vs. yoke position, relative to flight phase 0A:

	Scale Difference	Bias Difference
Phase 0A	0	0
Phase 0B	11 %	0.2 deg
ACTE Phase	7 %	2 deg

Flight Data Analysis

Effect of Instrumentation Differences on Analysis Results

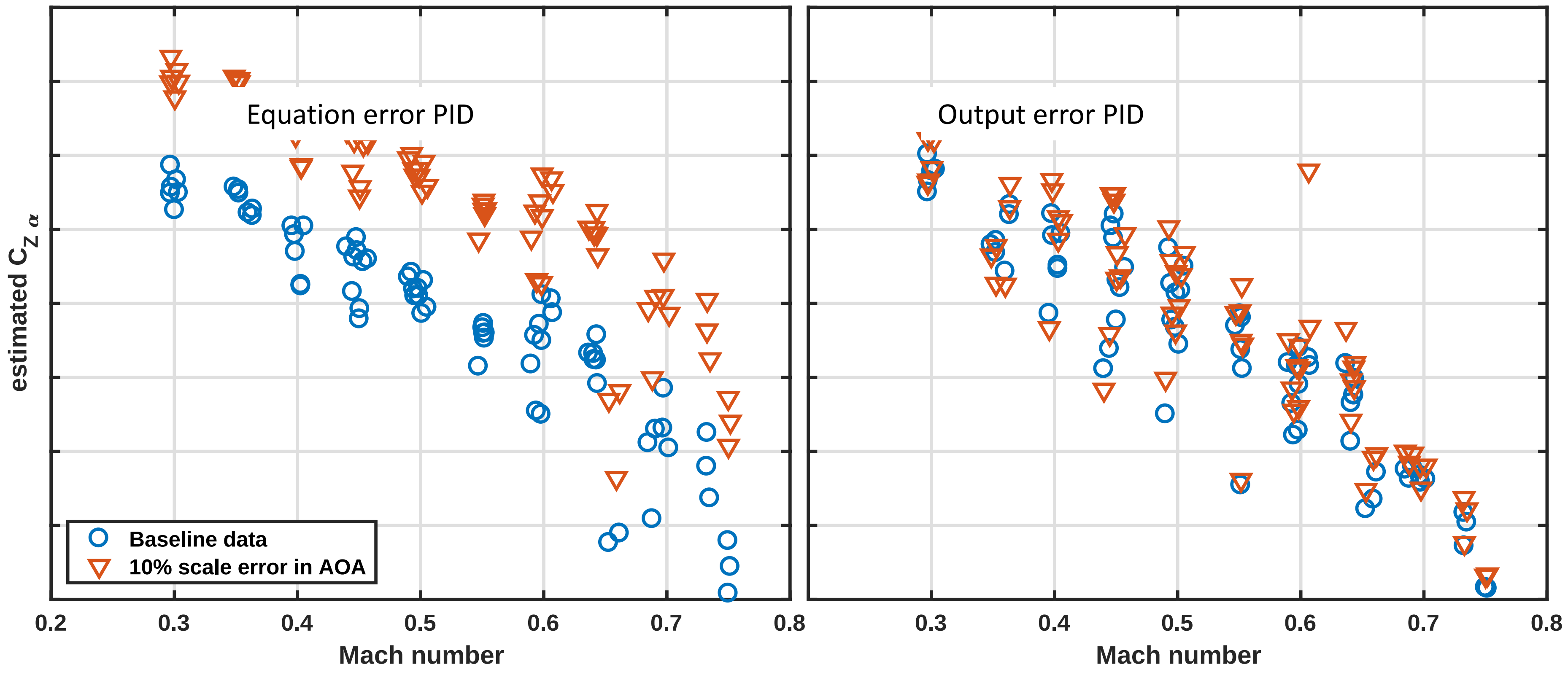


Aerodynamic Parameter Identification

- 90% of PID is data processing; the rest is the parameter identification
- Automate as much of the process as possible
  - Easier to make changes and try again
  - Allows for easy comparisons of signals and settings
- Correct your standard errors for colored residuals/Cramer-Rao bounds
  - Realize that your actual uncertainties are higher
- Use multiple parameter estimation techniques
  - Different techniques respond differently to noise, biases, time shifts, etc.
  - Differences in the parameter estimates can point out the existence of data errors
- Validate your pre-flight aerodynamic models and update them as-needed

Aerodynamic Parameter Identification

Equation error and output error PID can respond differently to measurement errors, such as scale errors in angle of attack



Publishing and Archiving

- Publications are a critical tool for effectively sharing knowledge, including best practices and lessons learned
  - Publish to the widest dissemination possible
  - Even if you can't publish openly, publish where you can (e.g., secure conference, NASA TM, internal report, etc.)
  - Include both successes and lessons learned
- Thorough archiving and appropriate storage of flight data will pay dividends
  - You never know when your flight data will be utilized
  - Include metadata to the maximum extent possible
  - Document analyses performed to convert raw data to engineering data
  - Detail flight test techniques

Concluding Thoughts

- Flight research, especially with one-of-a-kind aircraft, is difficult
- Documentation is important
- Lessons are learned (and often relearned) in every flight program

Questions?

Thanks:

Mike Frederick, Mark Davis, Trong Bui, Mark Smith, and Dan Banks