NASA/CP-2004-213028/PT1

COMSAC: Computational Methods for Stability and Control

Compiled by
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April 2004

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Proceedings of a symposium sponsored by the National Aeronautics
and Space Administration, Washington, DC, and
held at the Holiday Inn and Conference
Center, Hampton, Virginia
September 23-25, 2003

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April 2004

Acknowledgments

The organizing committee acknowledges the highly professional administrative contributions of Ms. Susan N. Price of the NASA Langley Management Support Office. In addition, the committee thanks Mr. Douglas N. Ball (Boeing Commercial Airplanes), Dr. Pradeep Raj (Lockheed Martin), and Mr. John W. Clark, Jr. (NAVAIR) for their participation in the COMSAC planning sessions, and for sharing their personal observations and opinions in the symposium.

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Executive Summary

A group of nearly 100 technical professionals from government, industry, and academia met in Hampton, Virginia on September 23-25, 2003, for a NASA-sponsored symposium on Computational Methods for Stability and Control (COMSAC) to discuss the status, opportunities, and challenges of applying Computational Fluid Dynamics (CFD) methodology to current and future issues in the field of aircraft stability and control (S&C). The unprecedented advances now being made in CFD technology have demonstrated the powerful capabilities of codes in applications to civil and military vehicles. Used in conjunction with wind-tunnel and flight investigations, many codes are now routinely used by designers in diverse applications such as aerodynamic performance predictions and propulsion integration. Typically, these codes are most reliable for attached, steady, and predominantly turbulent flows. As a result of increasing reliability and confidence in CFD, wind-tunnel testing for some new configurations has been substantially reduced in key areas, such as wing trade studies for mission performance guarantees.

Interest is now growing in the application of CFD methods to other critical design challenges. One of the most important disciplinary elements for civil and military aircraft is S&C. Experience has shown that predictions and analyses of aerodynamic S&C characteristics for full-scale aircraft can be in serious error because of Reynolds number effects, configuration sensitivities, dynamic motion effects, and other issues. Existing experimental facilities may not even be capable of replicating the motions required for aerodynamic measurements. As a result of these shortcomings, a major portion of aircraft development wind-tunnel time (about 60-70%) is typically devoted to S&C testing, especially for various off-design conditions ranging from takeoff and landing to cruise and maneuver. Even with an enormous amount of experimental work, pre-flight aerodynamic prediction errors result in unacceptable increases in program costs, "fly and try" approaches to fixing deficiencies, and extensive developmental delays. Unfortunately, applications of current and emerging CFD codes to engineering analysis in the field of aircraft S&C have been extremely limited. Although isolated examples of success have been demonstrated for certain configurations, the more global issues in S&C – which may involve massive flow separation, unsteady and nonlinear phenomena, dynamic effects, and other extremely complex factors – have not yet been significantly addressed by the CFD community. The current lack of COMSAC-related activities has been further aggravated by the fact that, in contrast to the areas of CFD and performance, very little cross-cultural interaction and communication appears to occur between participants in the areas of CFD and S&C. Within the aerospace community, it is generally agreed that the field of CFD has rapidly matured to the point that the next high payoff applications could occur in S&C. In particular, CFD offers the potential for significantly increasing the basic understanding, prediction, and control of flow phenomena associated with requirements for satisfactory aircraft handling characteristics.

The objectives of the 3-day symposium were to:

1. Discuss the unique aerodynamic phenomena and issues of S&C
2. Define the current characteristics, capabilities, and limitations of CFD codes
3. Define additional or new code requirements for S&C applications

4. Identify potential approaches to develop validated codes
5. Discuss the potential contents and funding opportunities for a COMSAC program

The scope of technical discussions covered civil and military aircraft, including commercial transports, business jets, fighter and attack aircraft, military transports, and bombers. Discussions were limited to fixed-wing aircraft. All sessions were unclassified, and all non-proprietary presentations were collated in the form of PowerPoint presentations with note pages for post-meeting distribution to attendees.

Presentations by speakers described numerous examples of severe impacts of erroneous aerodynamic predictions on the stability and control characteristics of civil and military aircraft. Typically, resolving and mitigating unexpected aerodynamic behavior involved laborious "cut and fly" approaches required during critical flight test programs. These shortcomings resulted in significant program delays, costs, mission limitations, non-optimum configurations (weight, capabilities, etc.), and severe scrutiny by stakeholders and customers.

In-depth discussions of specific experiences with actual applications of various levels of computational methods to S&C indicated a wide range of success and an overriding sense of skepticism by the attendees. After individual presentations were made to provide organizational and individual perspectives on CFD for S&C, the attendees were briefed on NASA's vision of a COMSAC program. Comments were solicited to identify and prioritize technology areas for such a program. Finally, the Director of the NASA-Langley Aerospace Vehicle Systems Technology Office shared his view of a potential strategy to augment funding and program priority in this area.

The general findings of the workshop were:

1. Inaccurate prediction of aerodynamic stability and control parameters continues to have major cost and programmatic impacts in virtually every vehicle class. These impacts include unacceptable increases in program costs, "fly and try" approaches to fixing deficiencies, extensive developmental delays and profit losses due to delayed deliveries.

2. Prediction of the character of separated flows across the speed range (with the attendant issues of transition prediction, turbulence modeling, unsteady flows, etc.) and the impact of separated flow on aircraft S&C should receive priority in a COMSAC program.

3. A pervasive attitude of skepticism regarding the success of CFD applications to aircraft S&C issues (especially for preliminary and conceptual design) exists within the CFD community, as well as the S&C community.

4. The application of advanced and emerging CFD methods as design tools will be dependent on the accumulation and demonstrated success of experiences for both generic and specific aircraft configurations.

5. Issues regarding the CFD process (cost, time required, adaptive gridding requirements, error quantification, etc.) should be high priority targets for COMSAC efforts.

6. One of the most valuable contributions of the symposium was the mechanism to share perspectives and experiences between the diverse CFD specialists and S&C specialists. Prior to this meeting, communication between these two groups was extremely poor, resulting in a major barrier to the acceleration and acceptance of CFD methods for S&C applications.

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COMSAC SYMPOSIUM

Introductory Remarks

September 23, 2003

Dr. Darrel R. Tenney
Director for
Aerospace Vehicle Systems Technology Office
NASA Langley Research Center
Hampton, VA

NASA/DoD Aerodynamic Flight Prediction Workshop

Nov. 19-21, 2002 in Williamsburg, VA

Dan Murri Dave Evans Brian Lundy Steve Cook Brian Kramer Joe Laiosa Russ Killingsworth Charlie Wilson Ojars Skujins
Rich Wahlsom Rudowsky Ed Kraft Mike Fremaux Joe Chambers Frank Lynch Dale Lorincz Paul Waters
Pradeep Raj Lawrence Ash Mike Hemsch Neal Pfeiffer Dan Banks Steve Donaldson Mark Potsdam Mark Booher John Rundquist Jim Thomas
Bill Baker Sue Crotts Larry Leavitt John Roberts Doug Ball Marge Rick Hooker John Liu
Terry Britt Ajay Kumar Draper-Donley Dave Schuster Bill Sellers John Malone Frank Berrier Tom Lawrence
Donna Speller Bob Hall Deepak Om
Long Yip Hugo Gonzales Greg Addington James Chung
Tim Naumomicz Jennifer Hansen Megan McCluer Bob Stuever Tom Ratvasky
Jack Ralston Tony Antani Mark Potapczuk
Roger Clark Al Paris
Mike Bonner

General Findings

Aerodynamic Flight Prediction Workshop

Nov. 19-21, 2002 in Williamsburg, VA

Summary Of The NASA/DoD Workshop On Aerodynamic Flight Predictions

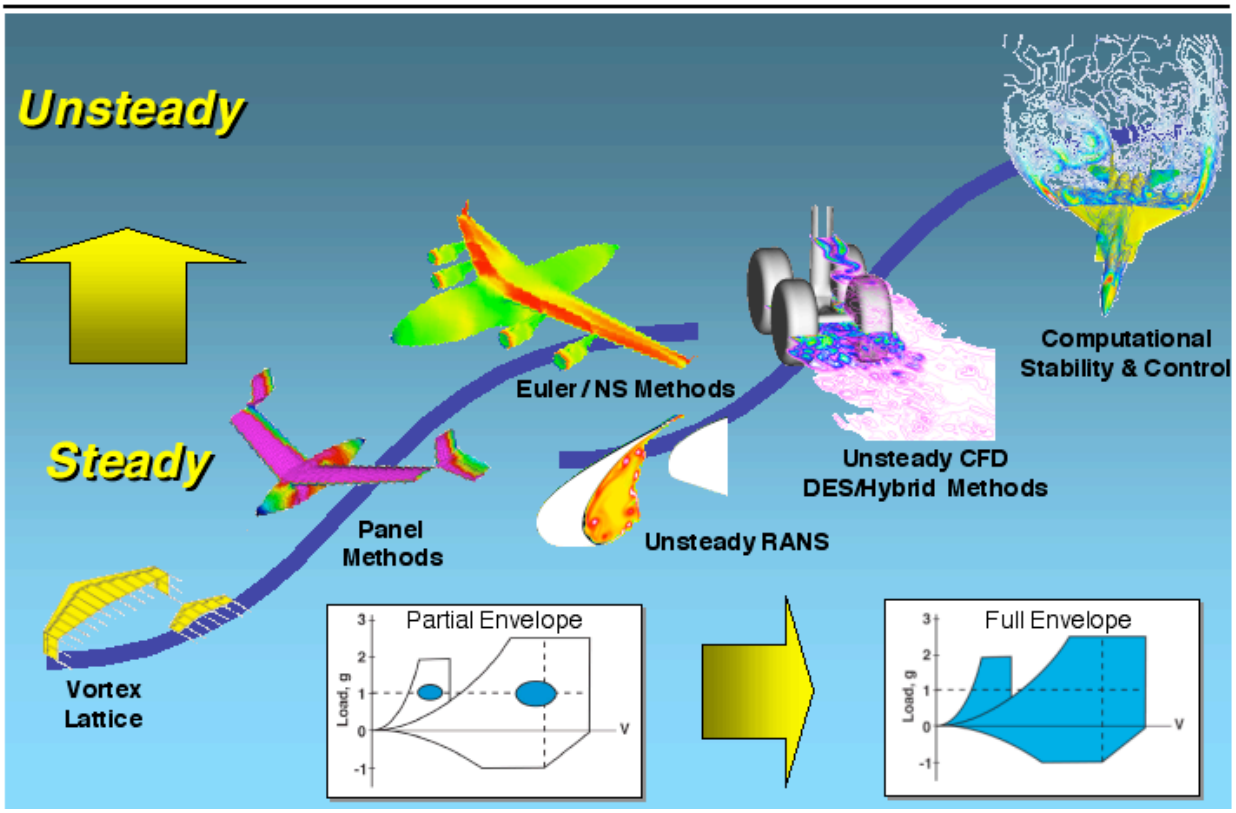
Williamsburg, VA
November 19-21, 2002

1. **Prediction of the onset of separated flows** across the speed range (with the attendant issues of transition prediction, turbulence modeling, unsteady flows, etc.) and the character and impact of separated flow on aircraft capabilities **is the single most critical fundamental issue to be addressed and should receive a very high priority in aerodynamic R&D programs**.

2. **The issue of Reynolds number impacts on aerodynamic predictions continues to pose significant barriers to advances in the state of the art.** The issues leading to this situation (cost, accuracies, operational difficulties, etc.) should be addressed with high priority.

3. **The loss of corporate knowledge and documentation of lessons learned in aerodynamic predictions is a major area of concern.** As a result of corporate mergers, large turnovers in staffs within government and industry, and fewer aircraft programs, the nation is rapidly losing its cornerstone experience base for the future.

Future Aerodynamic Prediction Requirements



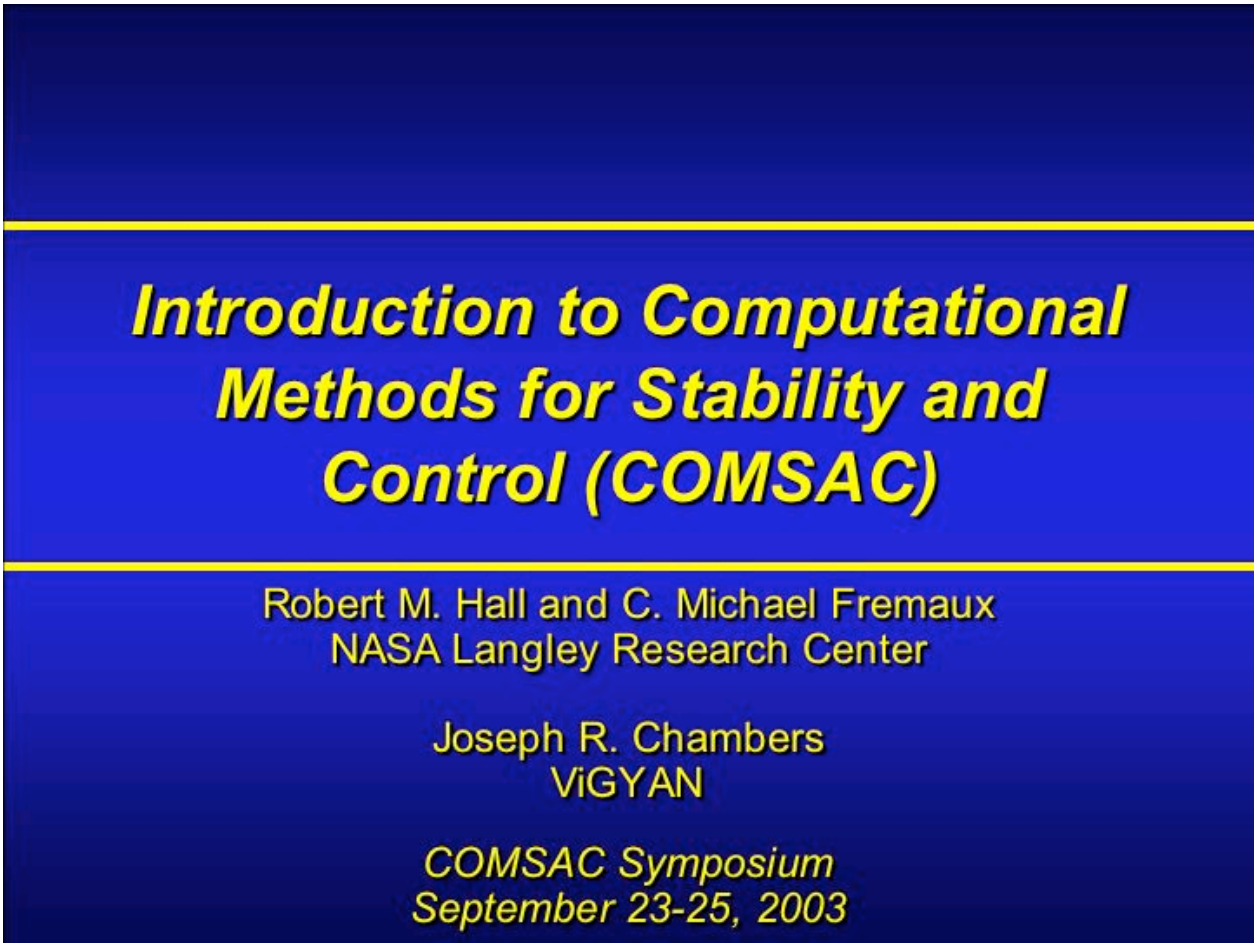
Concluding Remarks

- Future vehicle designs will see a paradigm shift from
  - Steady to the unsteady world (e.g. flow control, adaptive morphing),
  - Passive to active,
  - Rigid designs to exploitation of flexibility and adaptability
  - Few discrete to numerous distributed (e.g. sensors, control surfaces)
  - To obtain a vehicle that is always at optimum performance.

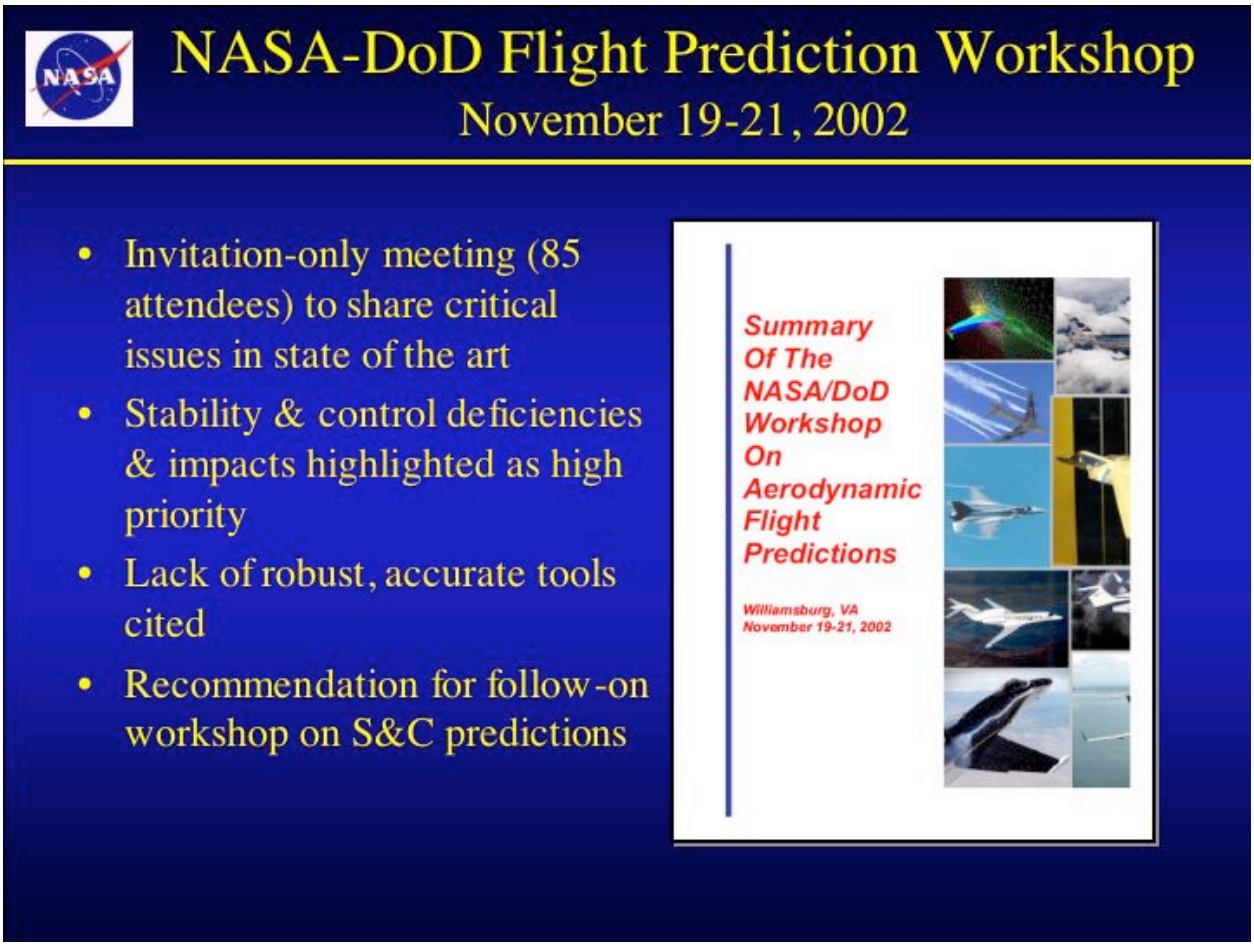
- Therefore, future designs will be inherently multidisciplinary, and the greatest technical challenges and opportunities occur at the intersection of disciplines

- COMSAC appears to be a step towards enabling the future vision

This Symposium is intended to bring together the often distinct cultures of the Stability and Control (S&C) community and the Computational Fluid Dynamics (CFD) community. The COMSAC program is itself a new effort by NASA Langley to accelerate the application of high-end CFD methodologies to the demanding job of predicting stability and control characteristics of aircraft. This talk is intended to set the stage for needing a program like COMSAC. It is not intended to give details of the program itself.



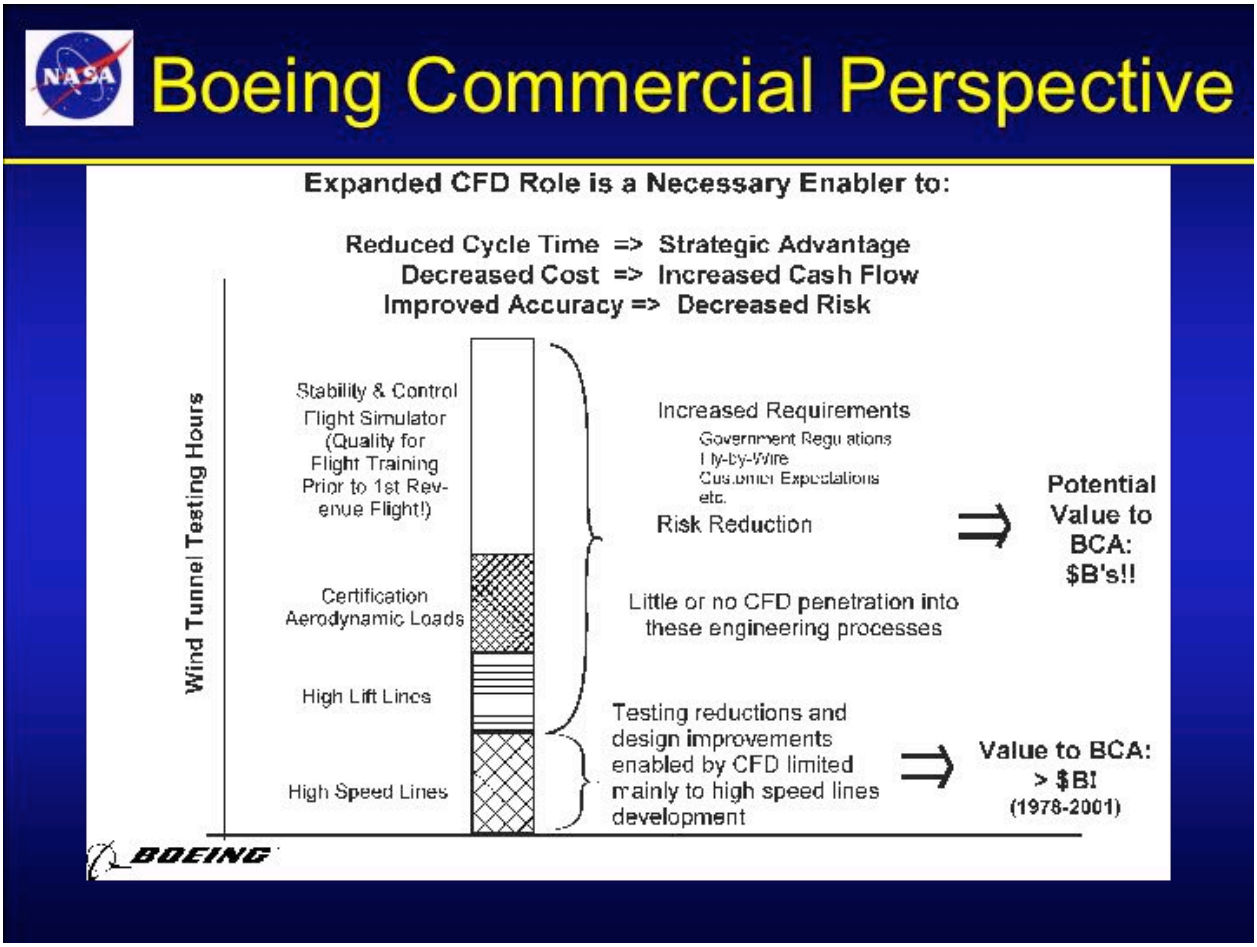
While there are many reasons to have this Symposium, a direct motivation for this event was the Flight Prediction Workshop.



Outline

- S&C challenges
- Aero prediction methodology
- CFD applications
- NASA COMSAC planning
- Objectives of symposium
- Closing remarks

This chart, by Doug Ball of Boeing Commercial, highlights the large amount of wind tunnel resources that are dedicated to determining stability and control characteristics, certification requirements, and low-speed lines. CFD has not generally penetrated these needs areas.



Impacts occur across of vehicle classes--767,F/A-18E, C130J, T-45,X-43 Stack, 777, Lear 23, AV-8B, and 737NG.

- 767--Stall for 767-400 model with raked tips more rapid than expected--vortilon pattern had to be developed
- F/A-18E--wing drop at transonic speeds. Impact: program almost canceled.
- C-130J--wing drop due to propeller induced effects. Impact: delayed deliveries, increased development costs
- T-45--low speed approach wing drop. Impact: redesigned wing
- X-43 Stack--inaccuracies of S&C aero data base. Impact: lost research vehicle

- 777--missed horizontal tail effectiveness. Impact: larger than needed horizontal
- Lear 23--Laminar separation bubble breakdown leading to wing drop on approach. Impact: safety of flight, development costs
- AV8B--wing drop and wing rock. Impact on operational envelopes (considered minimal)
- 737--737NG (400 to 800) sensitivity to wing rigging with unacceptable number of aircraft not passing acceptance flights. Impact: production expenses and development costs

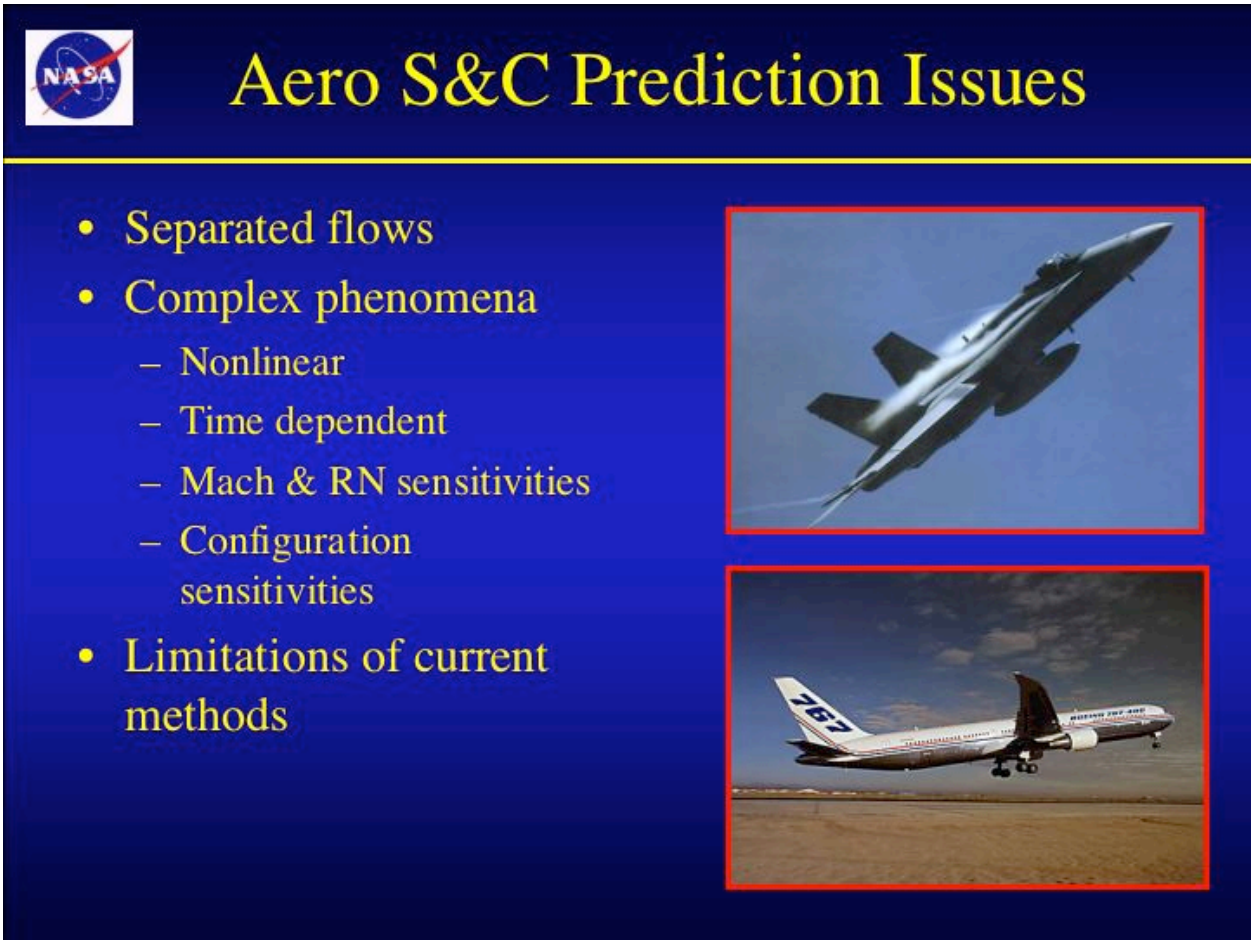
Results of Unpredicted S&C

- Unexpected development activities
  - Wind-tunnel tests
  - Flight tests
  - Flight controls
- Non-optimum modifications or operational limitations
- Delayed delivery schedules
- Increased development costs

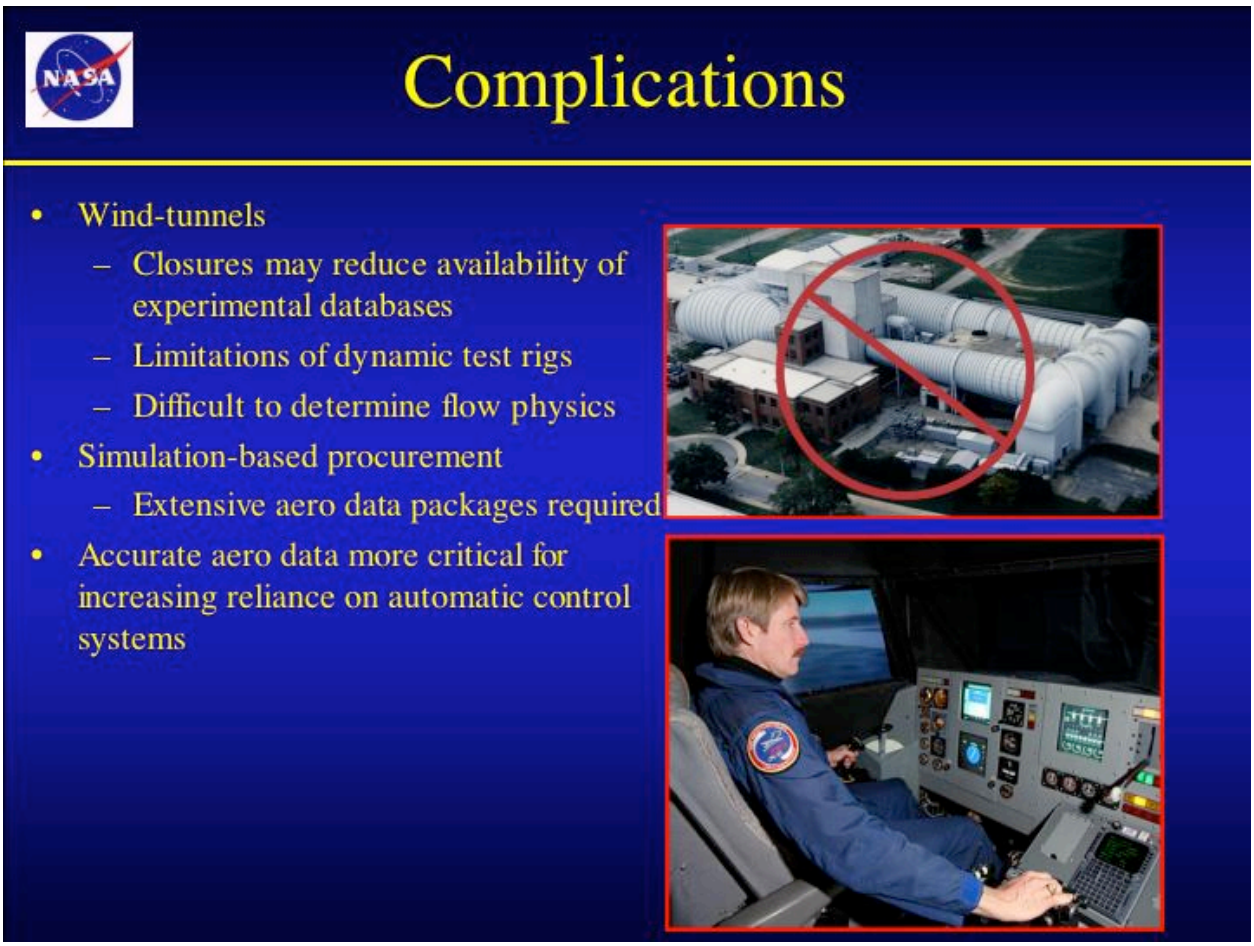
S&C Challenges

- S&C is a key enabling technology for all vehicle classes
- Major element in aircraft development programs
  - Over 65% of non-propulsion wind-tunnel test hours
  - Extensive piloted simulator studies
  - Major impact on design of flight controls
  - Requires unique test aircraft & flight tests
- Despite best practices, virtually <u>every</u> new aircraft program encounters unexpected aerodynamic S&C problems
  - Cut-and-try in flight solutions

Existing tools and methods for predicting characteristics when flow is primarily attached are adequate. However, when separation becomes significant, analytical tools are inadequate and CFD methods have not been calibrated, in general.



While wind tunnel availability is decreasing, needs for aero data bases are increasing. Computational tools will be needed to complement wind tunnel data to an increasing extent in the future.

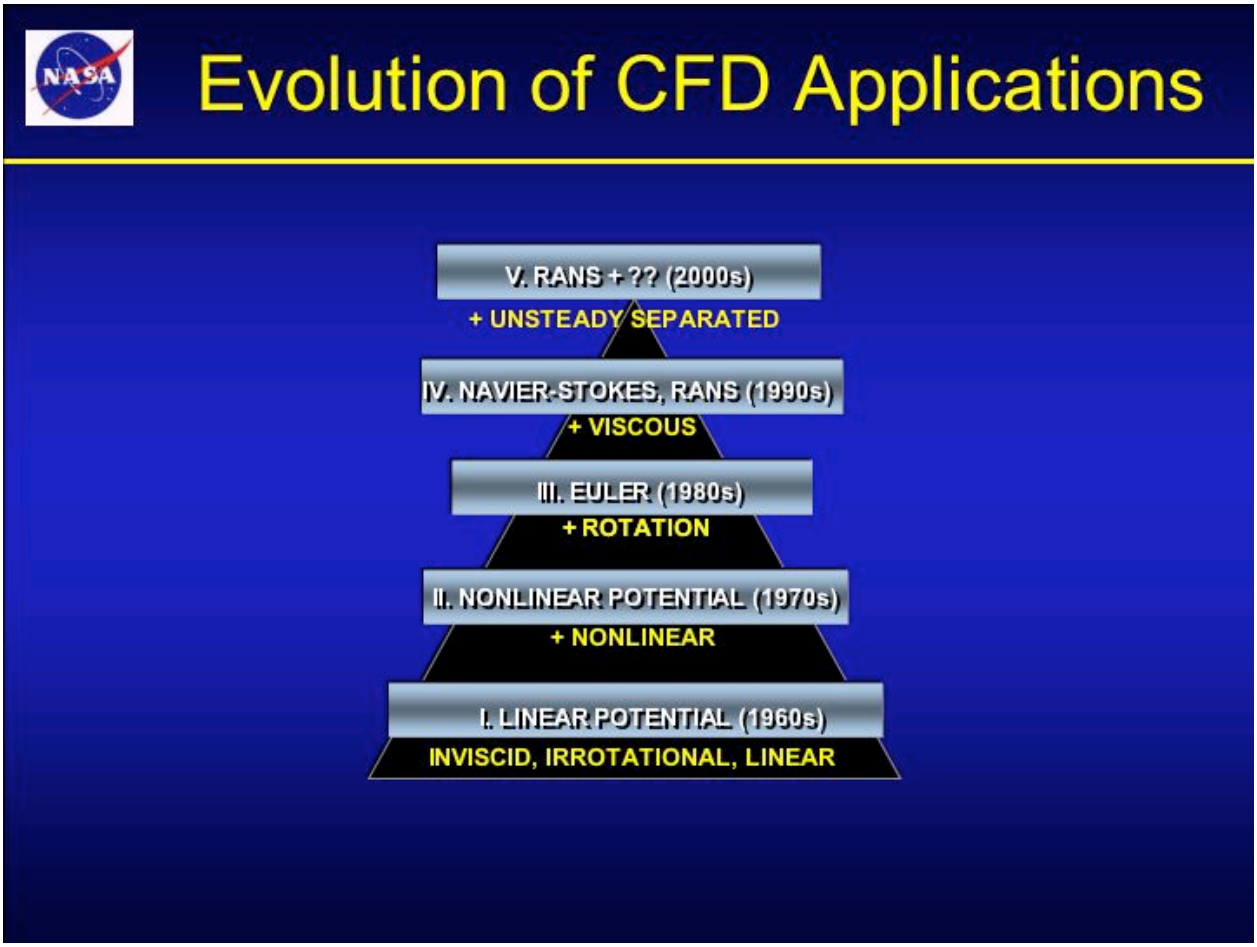


As will be reported in this Symposium, current and emerging CFD methods offer the exciting promise of new approaches to address the S&C needs. This will be even more important as emerging flow-control concepts are brought on line.

Future Opportunities

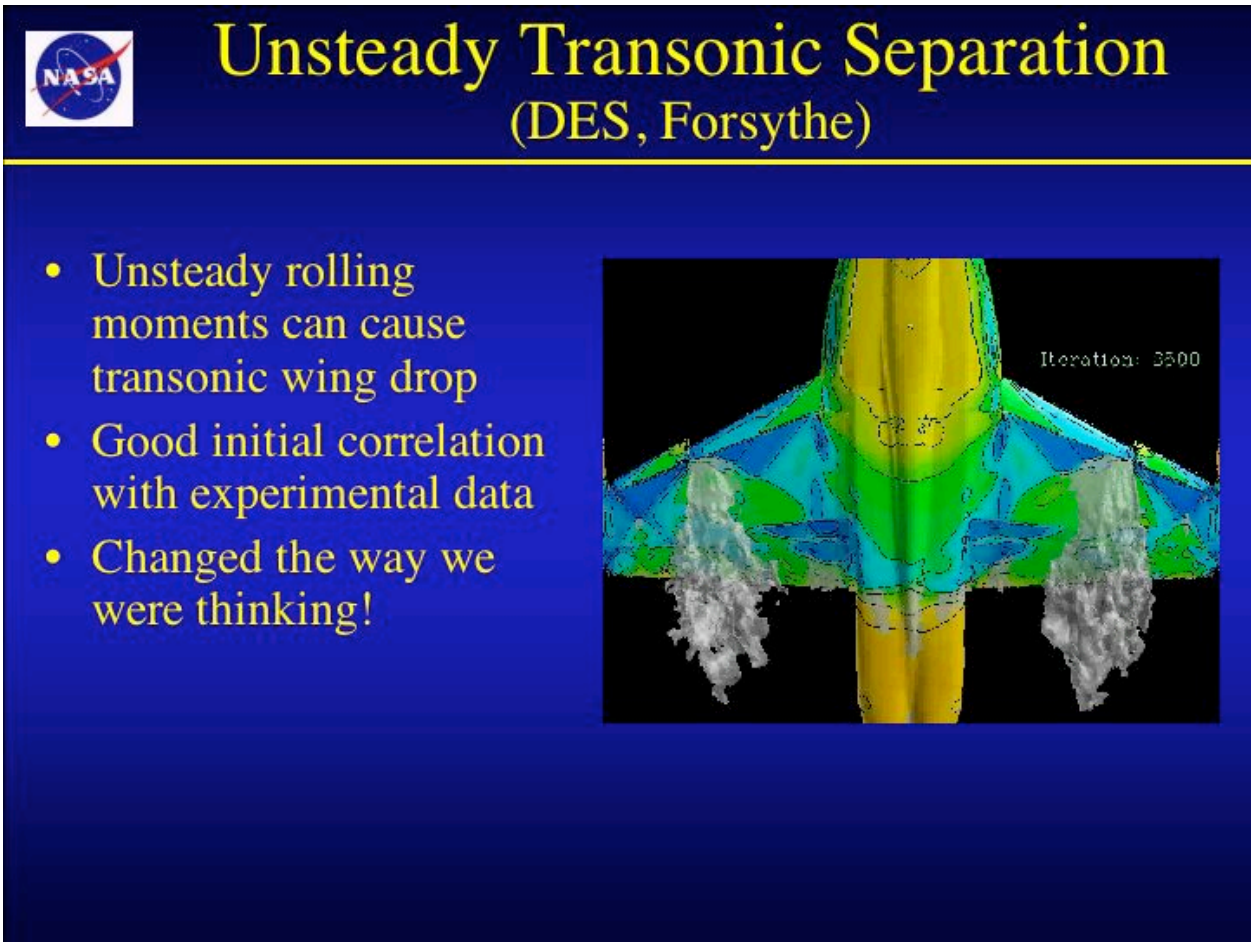
- Application of current & emerging CFD methods
- Emerging flow-control concepts
  - Active flow control
  - Smart structures
- We must understand flow physics to properly implement emerging concepts

The pyramid shows the general evolution of algorithms and computer power as a function of decade. The level V is labeled RANS+ because of the addition of methodologies such as either Large Eddy Simulation (LES) or Detached Eddy Simulation (DES). The bottom line is that there are new developments in algorithms which, when combined with increasing availability of computer resources, will enable the community to address problems that previously were untenable. The challenge now facing the CFD community is to take the latest levels of technology and begin making the sort of impacts in the stability and control arena that it has already made in the performance arena.

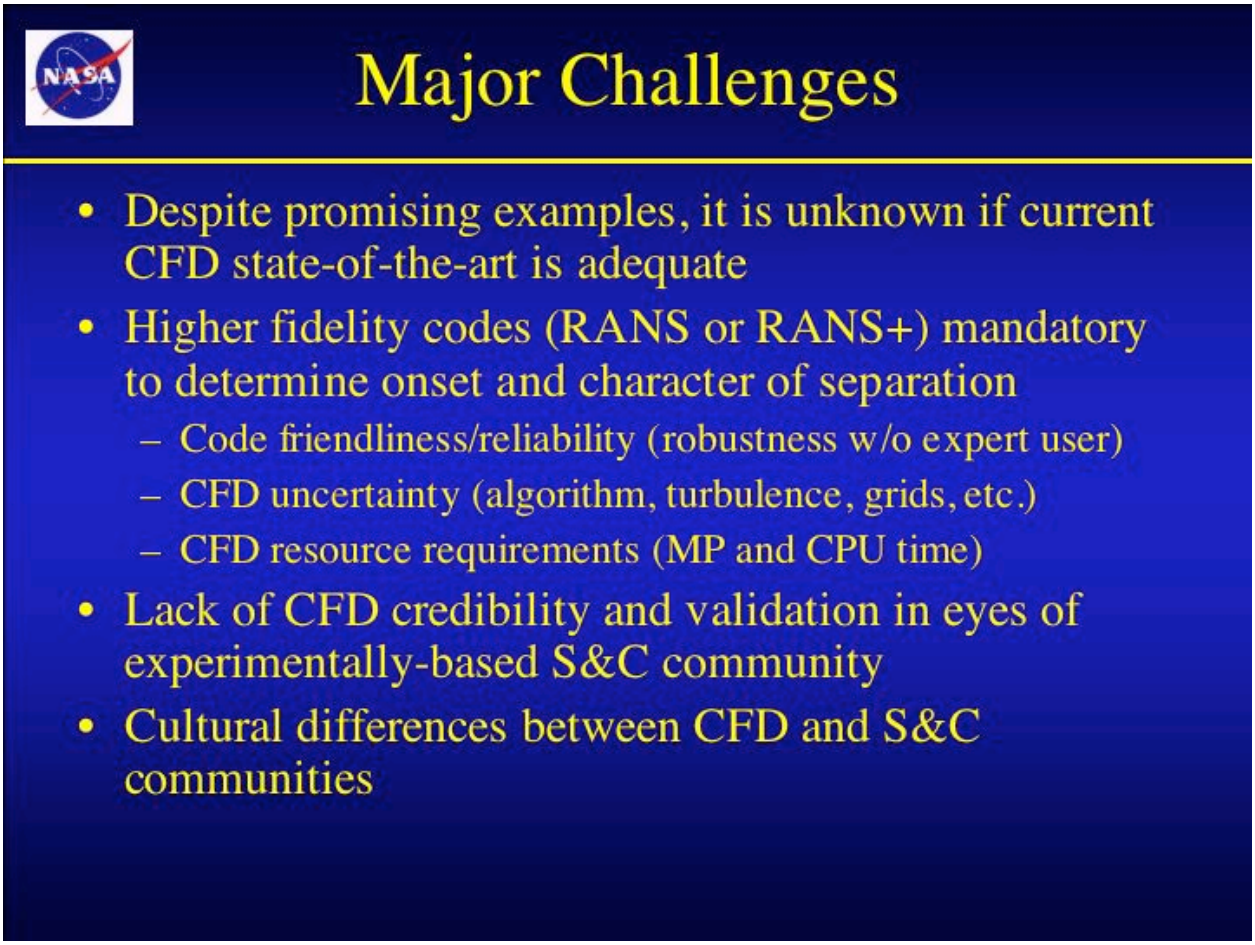


This list shows just a few of the many applications that have been addressed by the authors reporting during this Symposium. This is merely to communicate that a lot of work has already been done by a lot of organizations.

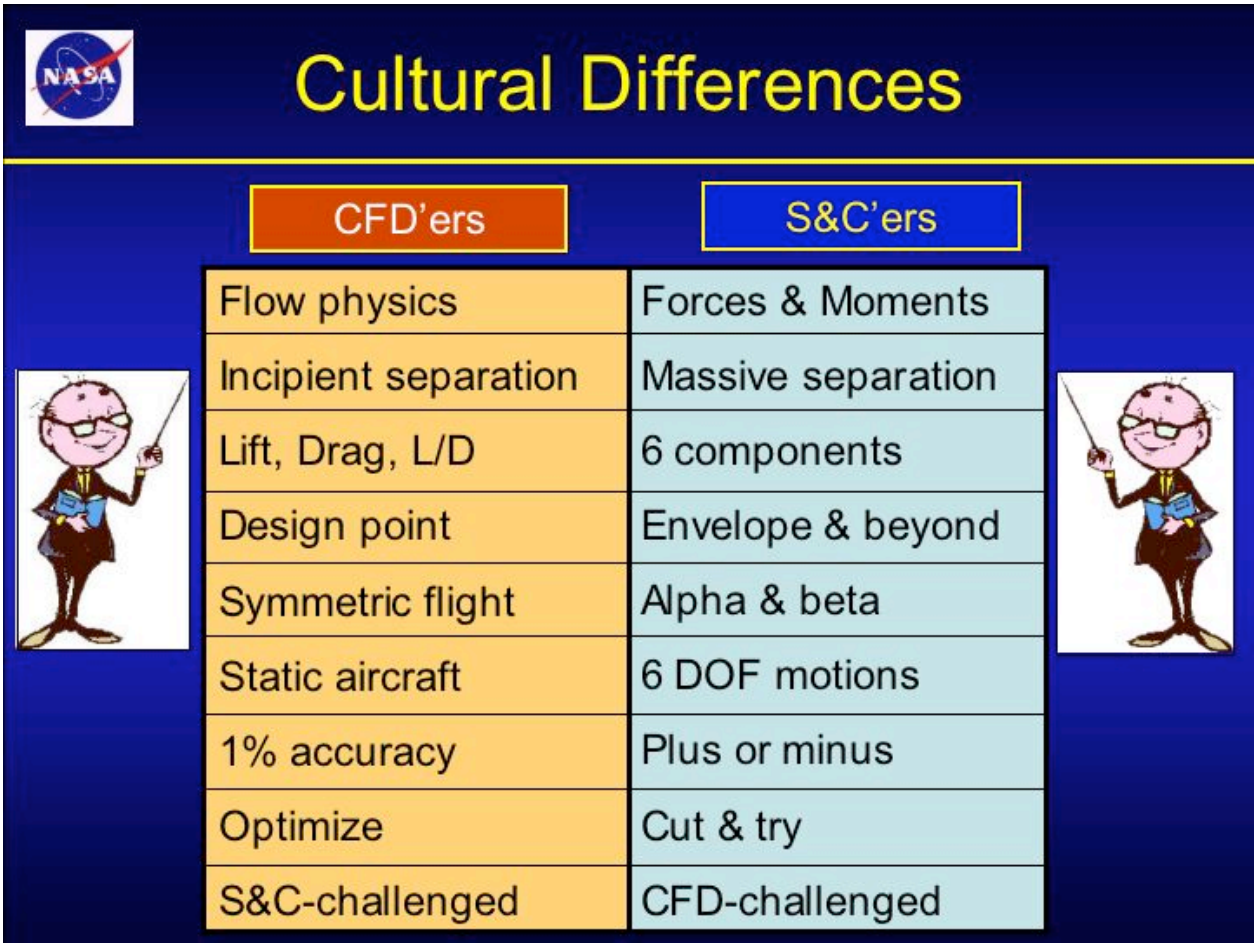
I would like to show one example with which I am familiar that comes from the Abrupt Wing Stall (AWS) program. This work was by Jim Forsythe and utilized a Detached Eddy Simulation (DES) implementation. The insight into the flow physics of this example changed the thinking of the S&C folks.



While there are examples of successes in applying CFD to S&C problems, it is still unclear within and outside of the CFD community that the current state-of-the-art is up to the task of predicting the very complicated, sometimes time dependent, flows associated with massively separated flows. What is clear, however, that it was appear that if separation is a large player in the flow field, it will be necessary to bring to the problem RANS or RANS+ levels of technology. This means that large resources will be required to address these problems. So ways will have to be found apply these codes with as much automation and robustness as possible. Of course, CFD credibility must be established in the S&C community by demonstrating that the codes can predict the answer before knowing it. Finally, while cultural differences are a challenge in bringing together the two disciplines, some of the reduced accuracy requirements associated with S&C may reduce some of the resource requirements.



This chart contrasts the differences between the two communities.



NASA has been involved with trips to different organizations to make sure we understood the level of technology and the needs of the communities.

NASA COMSAC Planning

- Industry & DoD tours
  - NAVAIR, Boeing Seattle, Lockheed-Martin Ft. Worth, Boeing St. Louis, Lockheed-Martin Marietta, AFRL
  - Most CFD applications focused on "9-1-1" requests
  - Widespread skepticism of CFD's role as a design tool in both S&C and CFD communities!
- COMSAC vision and framework prepared

Objectives of Symposium

- Improve communications between diverse cultures
  - Inform CFD community of S&C challenges
  - Inform S&C community of CFD state-of-the-art
- Share visions
  - What should be done?
  - How should it be done?
- Provide critique for NASA planning

•Day 1 - Tuesday, September 23, 2003			•	•
•7:15 AM	•8:15 AM	•Sign-In for Badge and Workshop-Related Materials	•	•Coffee, Juice, & Light Breakfast
•8:15 AM	•8:30 AM	•Introductory Remarks	•Darrel Tenney, NASA	•Welcome
•8:30 AM	•9:00 AM	•Introduction to COMSAC	•Bob Hall, NASA	•Session 1: Overview Speakers Session Chair: Long Yip
•9:00 AM	•9:30 AM	•Critical S&C Issues and Outlook--NASA Perspective	•Mike Fremaux, NASA	
•9:30 AM	•10:00 AM	•Emerging CFD Capabilities and Outlook--NASA Perspective	•Bob Biedron/ Paul Pao/Jim Thomas, NASA	•
•10:00 AM	•10:15 AM	•Break	•	•
•10:15 AM	•11:00 AM	•Boeing Commercial Perspective	•Doug Ball, Boeing Seattle	•Session 2a: Perspectives & Experiences Session Chair: Bob Hall
•11:00 AM	•11:30 AM	•Northrop-Grumman Perspective	•Dale Lorincz, Northrop Grumman	
•11:30 AM	•12:00 PM	•Boeing Military Perspective	•Dave Evans, Boeing St. Louis	
•12:00 PM	•1:00 PM	• Lunch	•	•
•1:00 PM	•1:30 PM	•AFRL Perspective	•Bill Blake/William Thomas, AFRL	•Session 2b: Perspectives & Experiences Session Chair: Bob Hall
•1:30 PM	•2:00 PM	•Raytheon Perspective	•Neal Pfeiffer, Raytheon	
•2:00 PM	•2:15 PM	•Break	•	
•2:15 PM	•2:45 PM	•NAVAIR Perspective	•Tom Lawrence, NAVAIR	
•2:45 PM	•3:15 PM	•Lockheed Martin Perspective	•Pradeep Raj, Lockheed Martin	
•3:15 PM	•3:30 PM	•Break	•	•
•3:30 PM	•4:00 PM	•Boeing TacAir S&C Issues for CFD	•Bill Hollingsworth, Boeing St. Louis	•Session 3a: S&C Issues for CFD Session Chair: Mike Fremaux
•4:00 PM	•4:30 PM	•NAVAIR S&C Issues for CFD	•Steve Donaldson, NAVAIR	
•4:30 PM	•5:00 PM	•Lockheed Martin (LMTAS) S&C Issues for CFD	•Russ Killingsworth, Lockheed Martin	
•	•	•Dinner -- On Your Own		•

Day 2 - Wednesday, September 24, 2003				
7:30 AM	8:00 AM	Arrival		Coffee, Juice, & Light Breakfast
8:00 AM	8:45 AM	Issues, Challenges, and Payoff: A Boeing CFD User's Perspective	Dave Bogue/Ron Doll/Ray Lines, Boeing Seattle	**Session 3b: Vehicle Design Issues for CFD** **Session Chair: Doug Ball**
8:45 AM	9:15 AM	Computational Simulations for S&C Conceptual & Prelim Design	Bill Mason, Va. Tech.	
9:15 AM	9:45 AM	Perspective on Separating Dynamic Stability Derivatives Using CFD	Larry Green/Angela Spence, NASA	
9:45 AM	10:00 AM	break		
10:00 AM	10:30 AM	Boeing TacAir CFD Capabilities/Issues	David Stookesberry/Frank Berrier, Boeing St. Louis	**Session 4a: CFD State-of-the-Art for S&C** **Session Chairs: Jim Thomas and Bob Biedron**
10:30 AM	11:00 AM	NASA TetrUSS Capabilities for S&C	Neal Frink/Paresh Parikh, NASA	
11:00 AM	11:30 AM	CFD Simulations for S&C -- Boeing Commercial State of the Art	N. J. Yu, Boeing Seattle	
11:30 AM	11:45 AM	break		
11:45 AM	12:15 PM	Lockheed Martin (Marietta) CFD Technology Paper	Rick Hooker, Lockheed Martin	
12:15 PM	12:45 PM	Time Dependent Calculations for S&C using OVERFLOW	Paul Pao/Pieter Buning, NASA Langley	
12:45 PM	1:45 PM	**Lunch**		
1:45 PM	2:15 PM	Application of COBALT to Abrupt Wing Stall using RANS and DES	Jim Forsythe, COBALT Solutions	**Session 4b: Application of CFD to S&C** **Session Chairs: Neal Frink and Larry Green**
2:15 PM	2:45 PM	Computational S&C Techniques for Unsteady & Aeroelastic Effects	Dave Schuster, John Edwards, NASA	
2:45 PM	3:00 PM	break		
3:00 PM	3:30 PM	Hinge Moment Predictions using CFD	Matt Grismer, AFRL	
3:30 PM	4:00 PM	CFD Simulation of Aircraft in Coning Motion	Syta Saephan, Case van Dam, UC Davis	
4:00 PM	4:15 PM	break		
4:15 PM	4:45 PM	Qualification of Large External Store Carriage for F-15 Using CFD	Jeff Batte, Eglin AFB	
4:45 PM	5:15 PM	CFD Predictions of Aircraft Fallling-Leaf Characteristics	Eric Charlton, Lockheed Martin	
6:30 PM	8:30 PM	**Group Dinner--Lecture entitled "The Challenge of Flying the World's First Aircraft"**	Colin Britcher, Old Dominion University	

Day 3 - Thursday, September 25, 2003				
7:30 AM	8:00 AM	Arrival		Coffee, Juice, & Light Breakfast
8:00 AM	8:30 AM	Uncertainty in Computational Aerodynamics	Mike Hemsch, Jim Luckring, Joe Morrison, NASA	**Session 5: Process and Validation** **Session Chair: Paul Pao**
8:30 AM	9:00 AM	A Best Practices System to Enhance CFD in S&C Applications	Mike Mendenhall, Nielsen Eng & Research	
9:00 AM	9:30 AM	Dynamic Water Tunnel Testing for Code Benchmarking	Brooke Smith, John Hodgkinson, AeroArts	
9:30 AM	9:45 AM	break		
9:45 AM	10:30 AM	NASA COMSAC "Strawman" Plan	Bob Hall, NASA	**Session 6: COMSAC: The Road Ahead** **Session Chairs: Bob Hall and Long Yip**
10:30 AM	10:45 AM	Prepared Roadmap Feedback	Pradeep Raj, Lockheed Martin	
10:45 AM	11:00 AM	Prepared Roadmap Feedback	John Clark, NAVAIR	
11:00 AM	11:15 AM	Prepared Roadmap Feedback	Doug Ball, Boeing Seattle	
11:15 AM	12:00 PM	Participant Feedback	All	
12:00 PM	12:15 PM	Summary and Wrap Up	Darrel Tenney, NASA	
12:15 PM	1:00 PM	**Lunch**		
1:00 PM	2:30 PM	Strategy for Advocacy	Darrel Tenney, NASA	**Session Chairs: Long Yip and Jim Pittman**

Closing Remarks

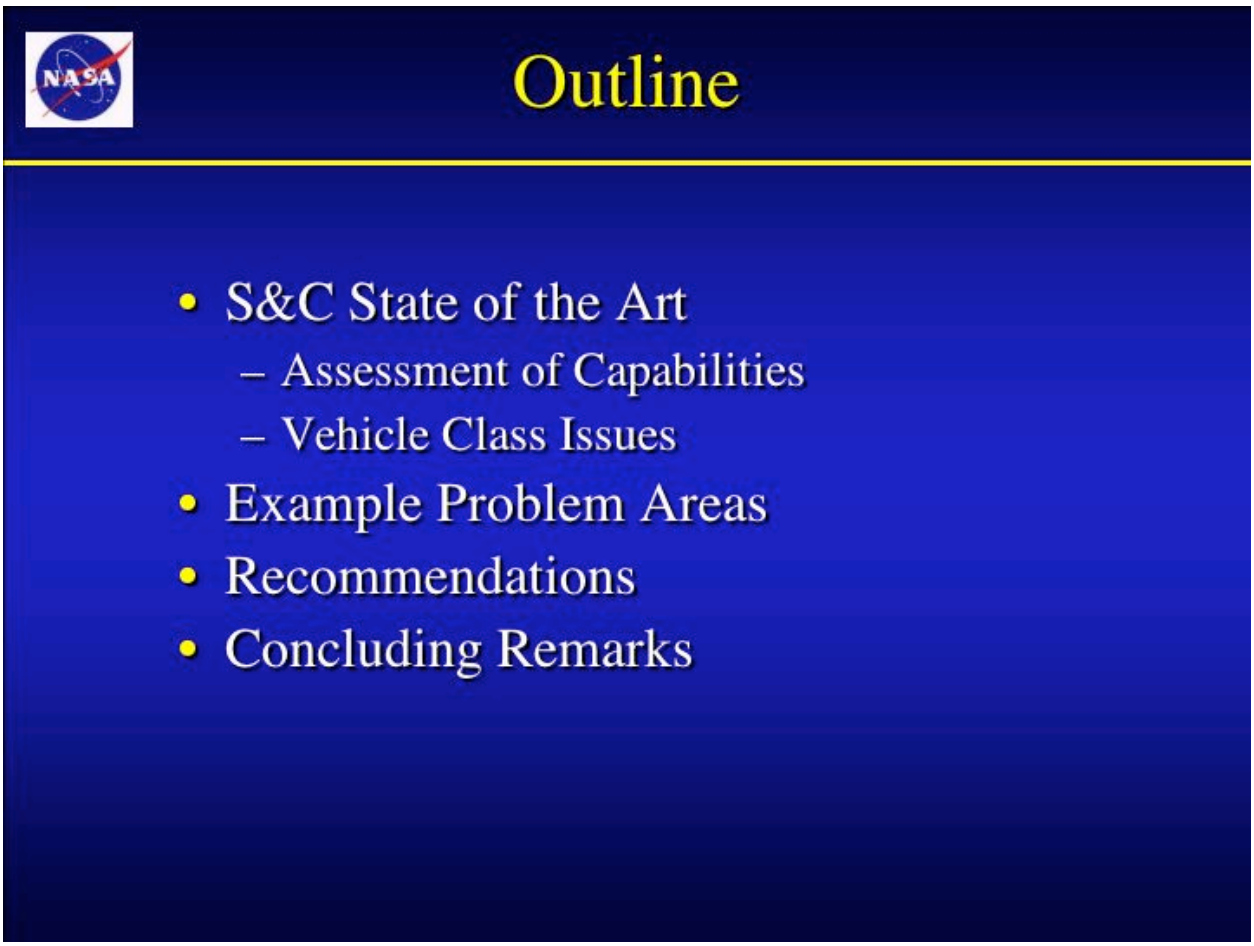
- The next major breakthrough in S&C capabilities will involve CFD
  - Sophistication & capabilities of CFD rapidly maturing
  - Barriers (cost, time, etc.) are rapidly falling
- Coordinated, focused effort will accelerate this process
  - NASA can not accomplish the formidable task alone
  - Seek your comments and guidance on how to proceed

Stability & Control Challenges for COMSAC: A NASA Langley Perspective

C. Michael Fremaux
NASA Langley Research Center

COMSAC Symposium
September 23, 2003

This presentation is designed as a limited-scope "tutorial" and is aimed primarily at the CFDer who has not been exposed to stability and control problems. Examples of some classic S&C problems are used for illustration.



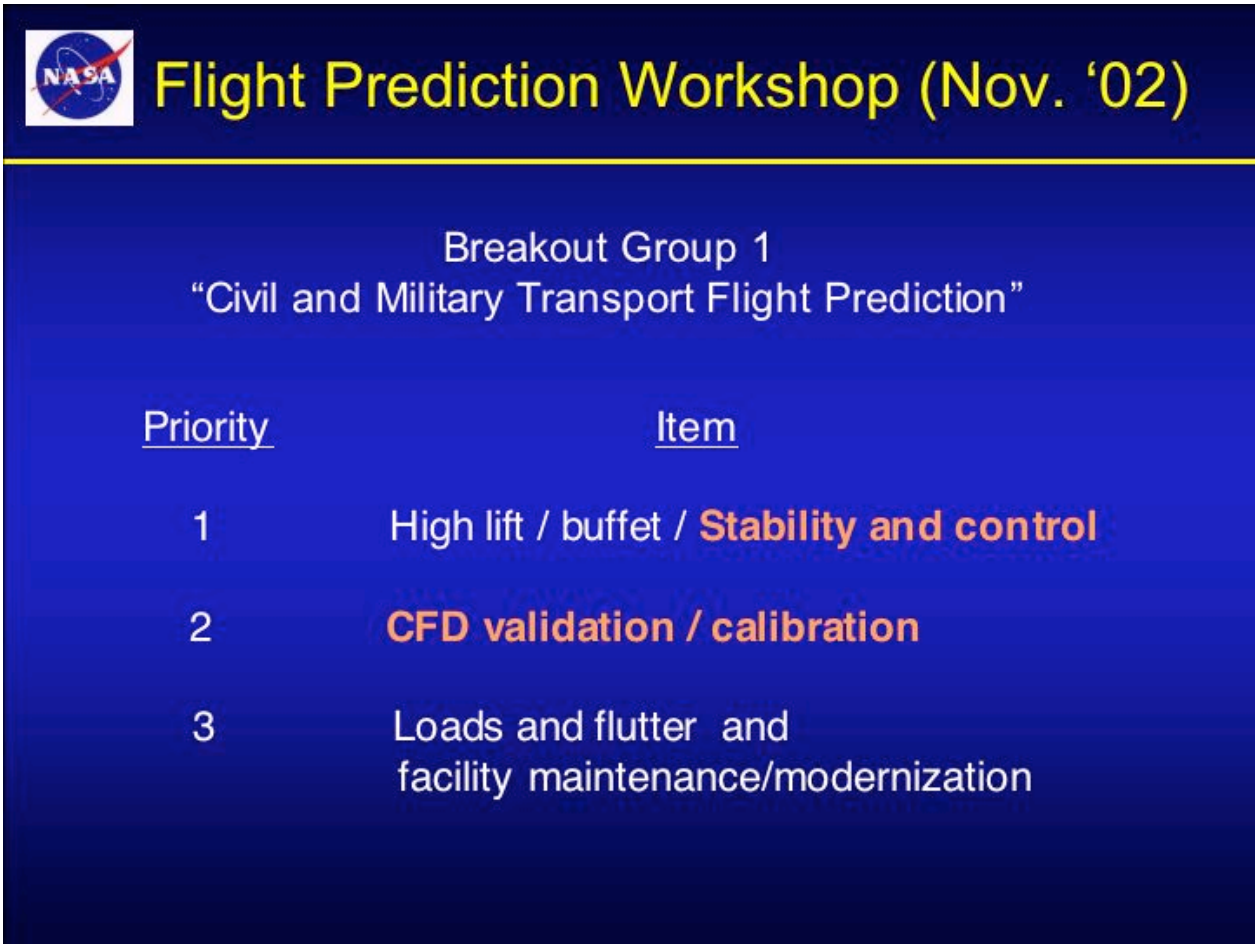
S&C is a fundamental technology for enabling flight, but significant problems with the prediction of S&C characteristics persists, especially where separated flow is involved.
Even after 100 years of flight, experimental methods still have significant limitations.
Experimental and computational tools can and must be complementary.

S&C State of the Art

- Stability and Control prediction is a *fundamental enabling technology* for any flight vehicle
- S&C experiments are often hampered by scale effects, rig limitations, and lack of flow physics information
  - Leads to unexpected results in flight
  - Impacts cost, schedule, potentially program survival
- The presence of separated flow in all but the most benign flight regimes can lead to unexpected (i.e. unsteady and/or non-linear) behavior and can make rapid, reliable prediction of S&C parameters a difficult task

CURRENT TOOLS HAVE SIGNIFICANT LIMITATIONS FOR CONSISTENTLY PROVIDING HIGH-QUALITY S&C DATA IN MANY FLIGHT REGIMES OF INTEREST

NASA Flight Prediction Workshop (Williamsburg, Virginia, November 2002) brought together experts from government, industry, and academia to discuss problems associated with state-of-the-art flight prediction. Among the concerns highlighted were deficiencies in S&C prediction lack of calibrated CFD tools for aerodynamic prediction in general.

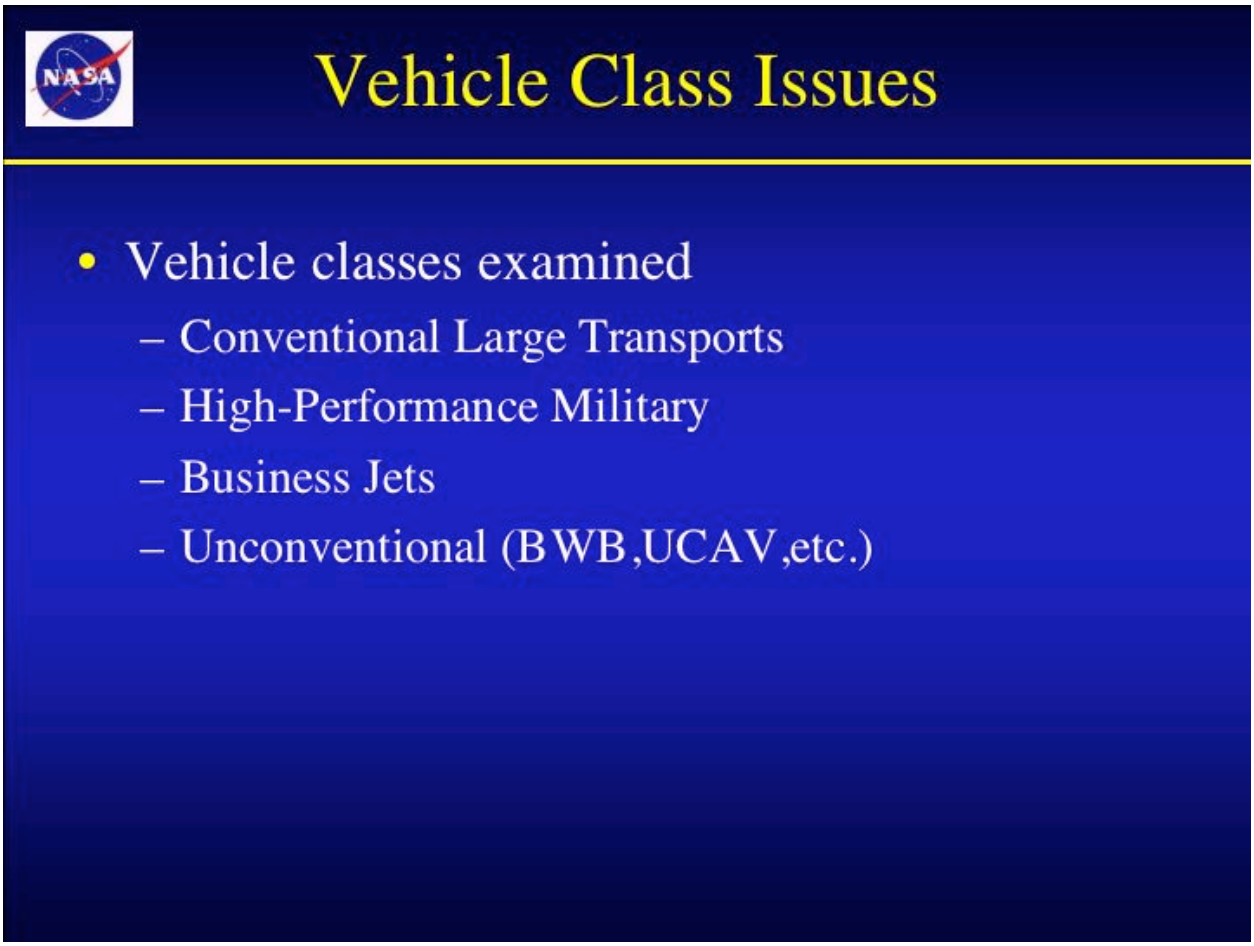


Some problem areas highlighted at the Flight Prediction Workshop, plus a few added by the author.

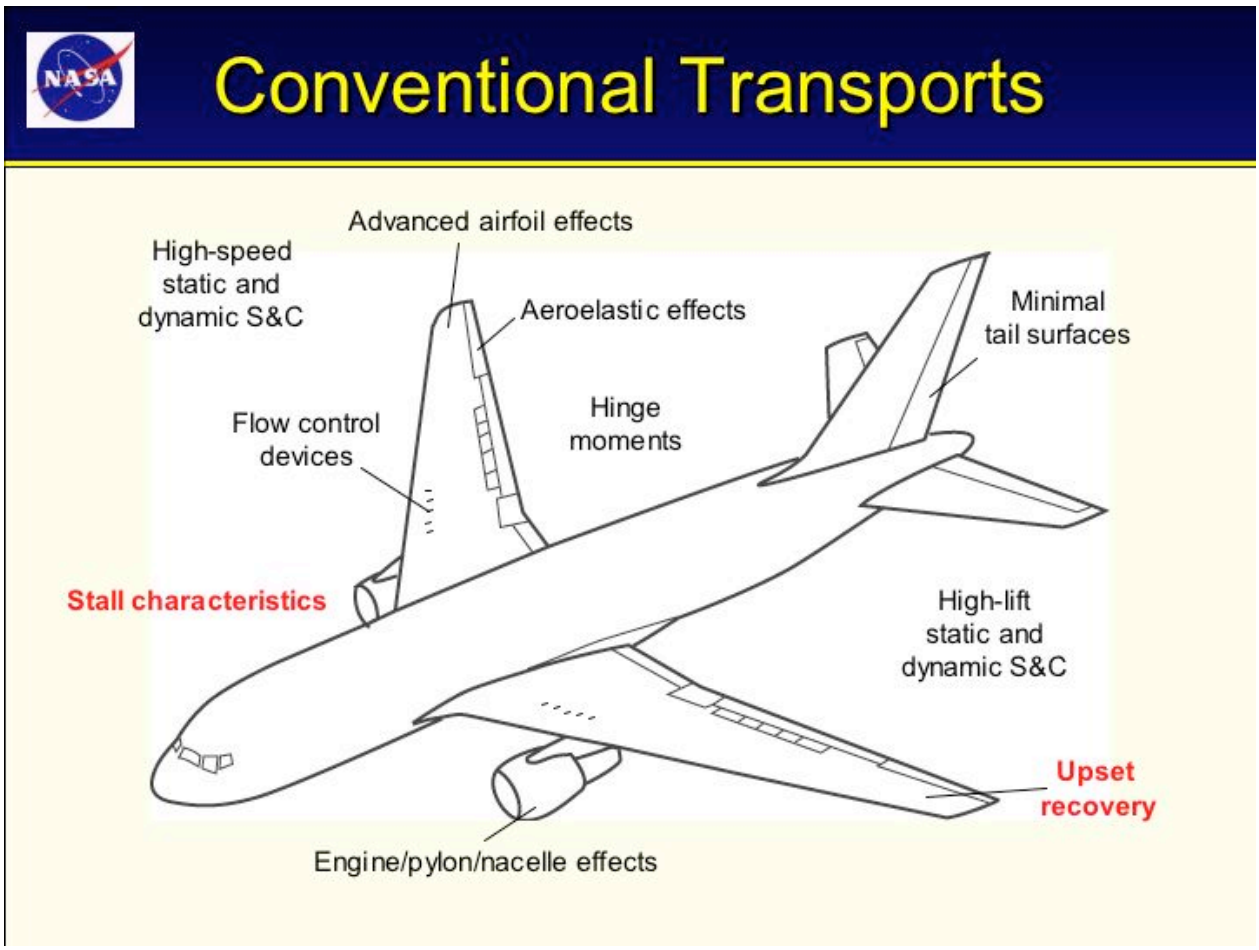
Stoplight Assessment of S&C Issues

"Improvements Needed"	"Critical Shortcomings; High Priority"
Jet Interactions (propulsion-induced effects)	Impact of Separated Flow
High-α Behavior/ Maneuverability--Low Speed	Transonic Characteristics (high α/β, damping, abrupt aero changes)
Dynamic Stability--Low Speed	STOVL Ground Effects--Static and Dynamic
Pitch Trim (e.g. Cm_o for L.O.)	Dynamic Loads
Out-of-control modes (spin, falling leaf, tumble, etc.)	Scale Effects (Rn and M) on Stability
Hinge Moments/Control Power	Interactions of Complex Controls (e.g. BWB)
High-lift S&C	Modeling--Unsteady and Non-linear

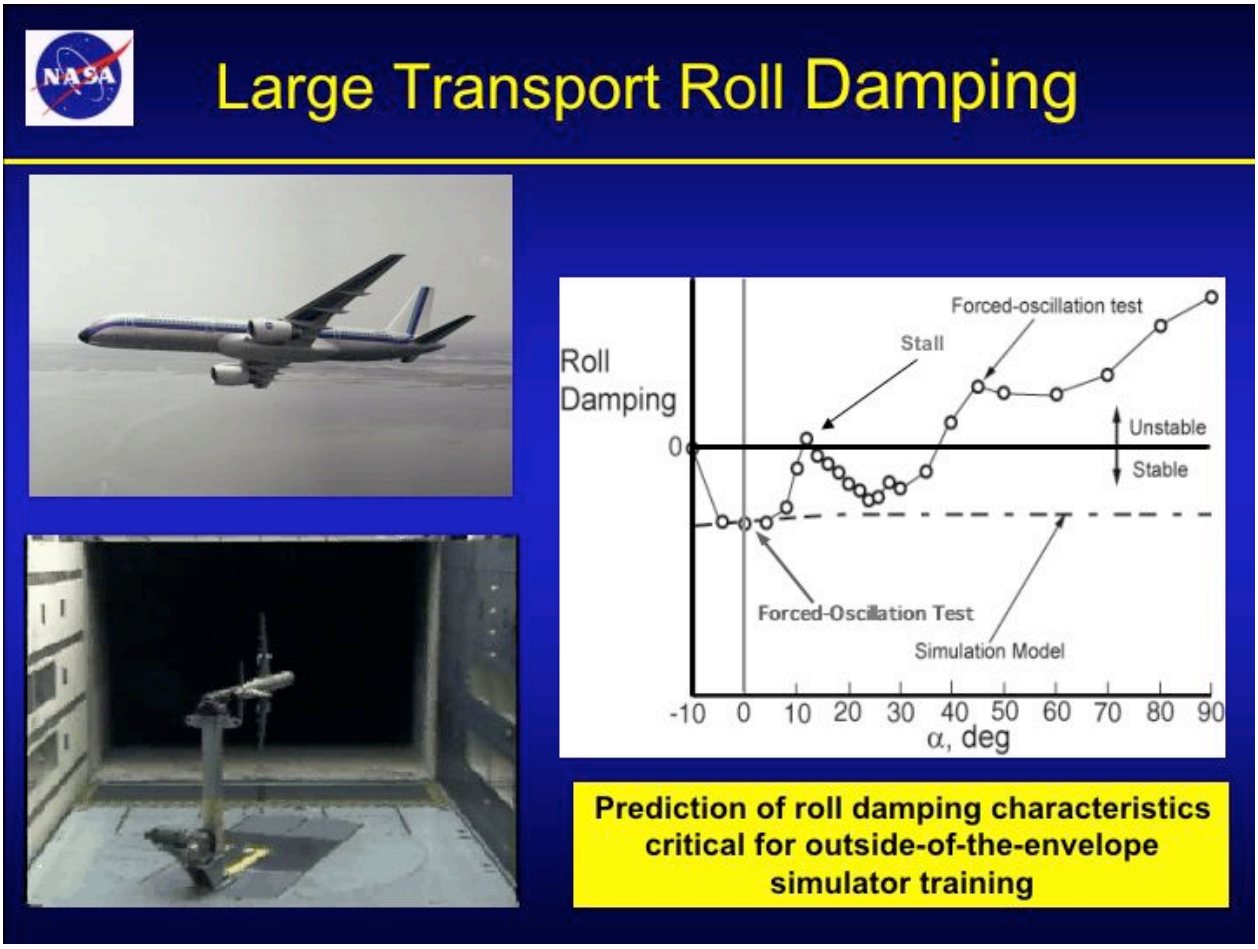
For illustration purposes, problem areas for four “vehicle classes” are examined.



Some issues typically associated with large transports. Items in red are highlighted in the example on the following page.

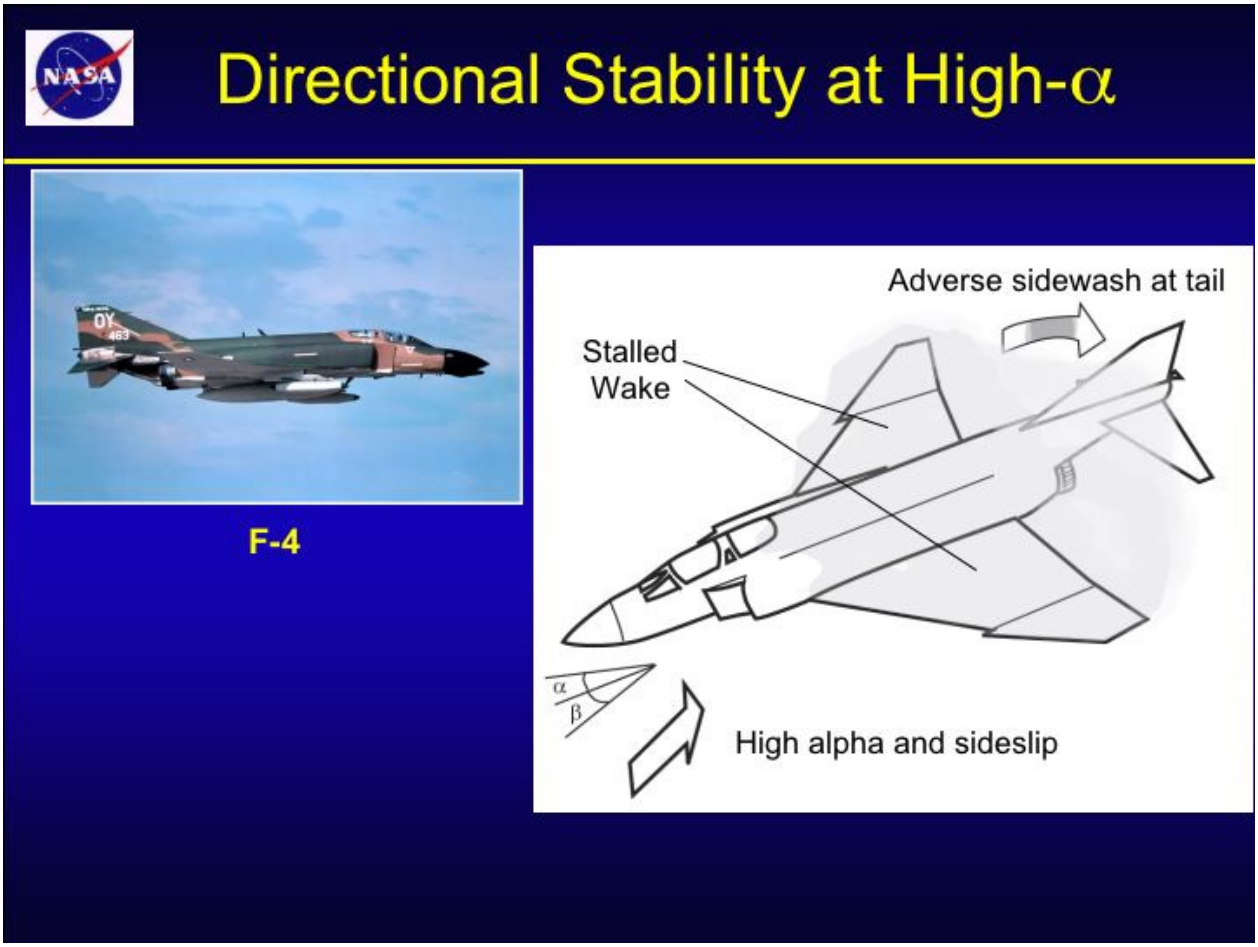


As illustrated by NASA Aviation Safety Program data, roll damping for a large jet transport predicted by the forced-oscillation technique in a wind tunnel is significantly different from that obtained by analytical or handbook methods (e.g. DATCOM), as illustrated by the "Simulation Model" curve. Wind tunnel data indicate that this configuration will have slightly unstable roll damping at stall and will be highly unstable in roll above about 40 degrees angle of attack. Training pilot for stalls and dealing with "out of control" upset conditions may be greatly improved by having better roll damping predictions for simulation.

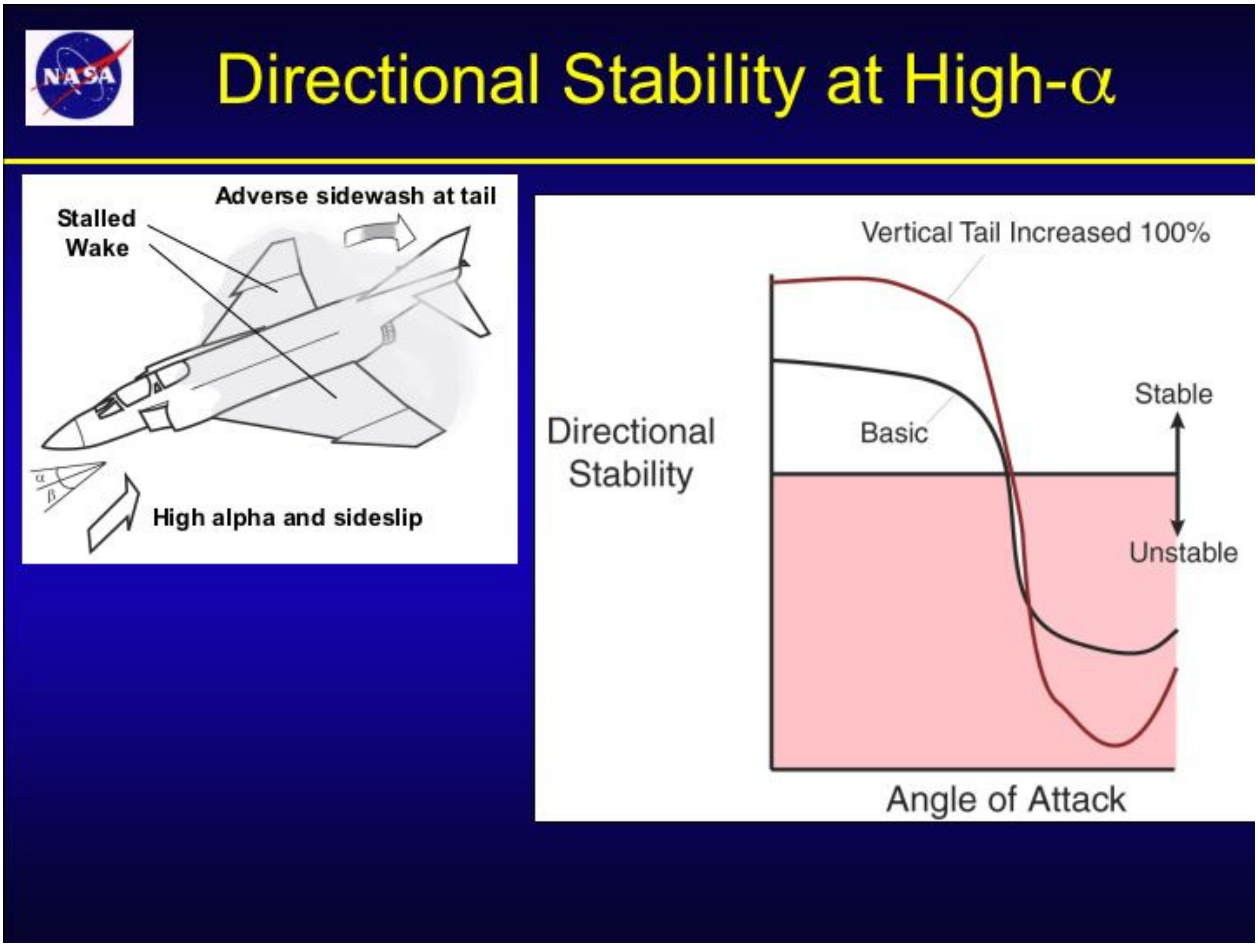


High performance airplanes can have many of the same issues as transports, but there are differences due to the configuration (e.g., sharp leading edge wings, highly swept leading-edge extensions (LEX) or strakes, and close-coupled control surfaces. The fact that these vehicles routinely maneuver at post-stall angles of attack means that flying with separated and vortical flow is the rule, not the exception. Transonic phenomena such as shock-induced wing drop or low-speed wing rock are also not uncommon.

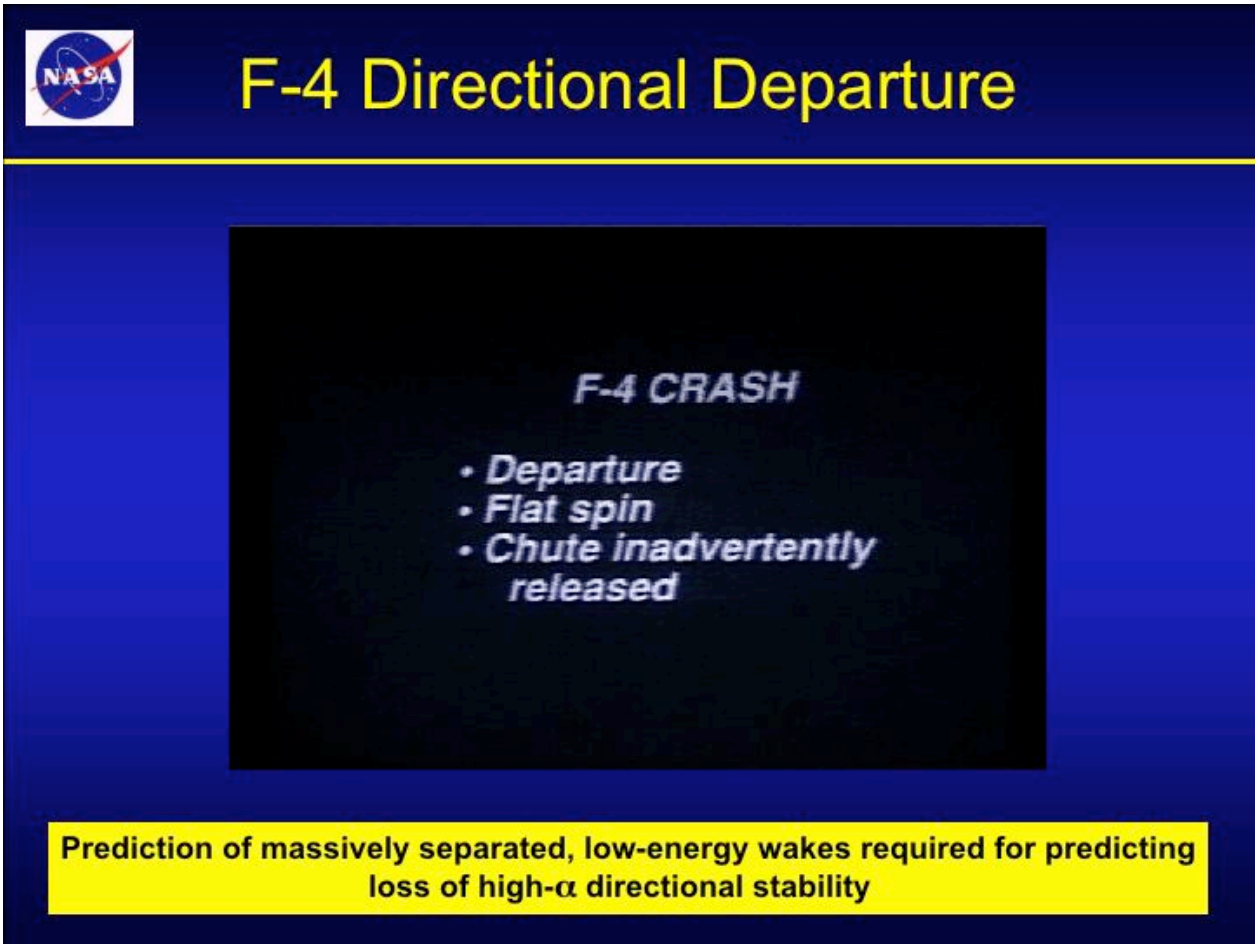
The F-4 was originally designed as a "missile shooter", not a high-α fighter. During the Vietnam conflict, they were engaged as close-in dogfighters and began suffering significant losses due to spin accidents resulting from loss of directional control at elevated angles of attack. Over 100 Navy and Air Force 100 F-4s were lost before the cause of the problem was identified and resolved by modifications to the leading edge of the wing (slats) to delay stall and improve stall warning. Adverse sidewash at the tail as a contributing factor to loss of directional stability was identified through wind tunnel tests.



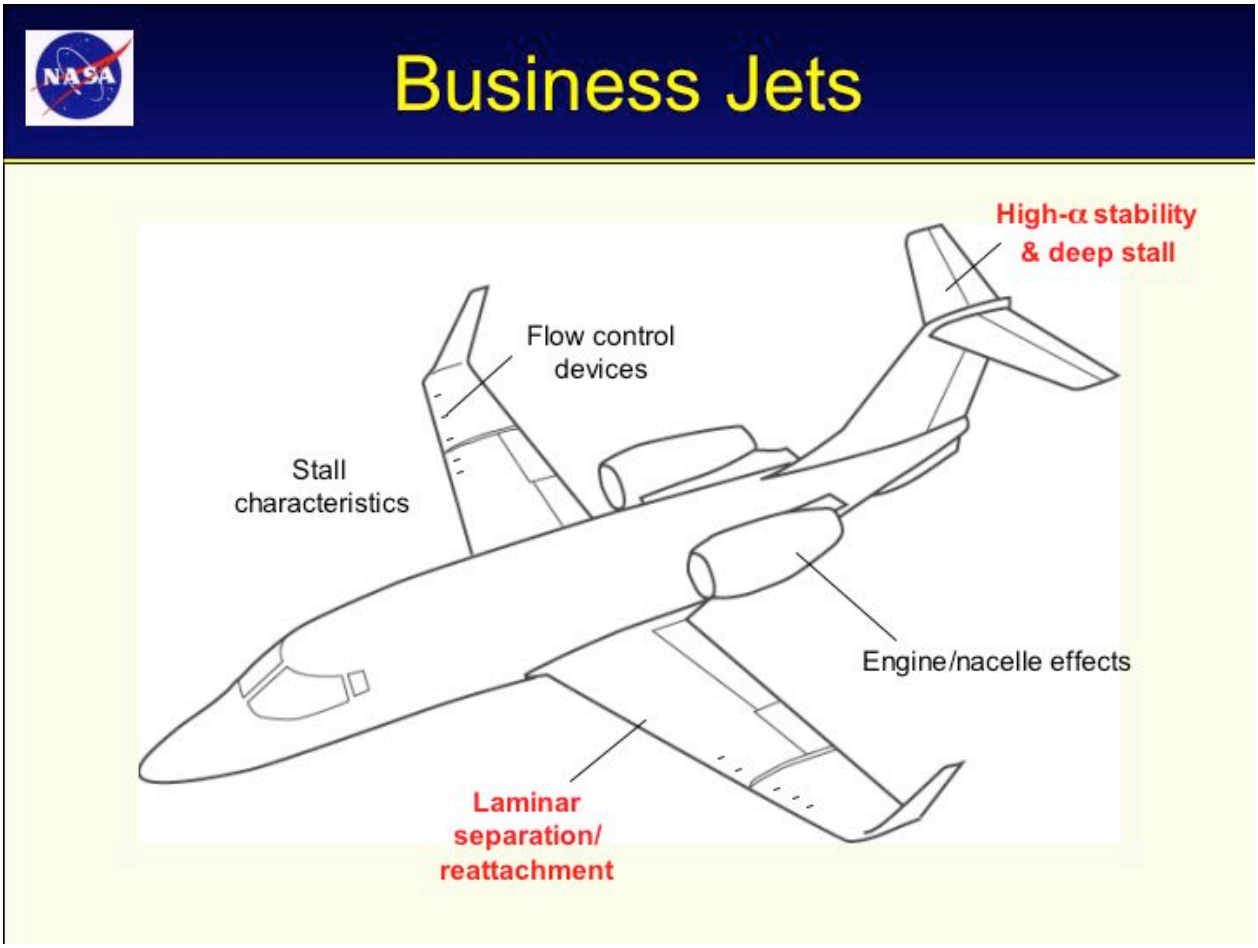
In this case, adding area to the vertical tail to improve directional stability helps for pre-stall angles of attack (i.e., prior to formation of the large wake from the stalled wing), as anticipated, but actually makes the directional instability worse at high angles of attack due to the adverse sidewash at the tail.



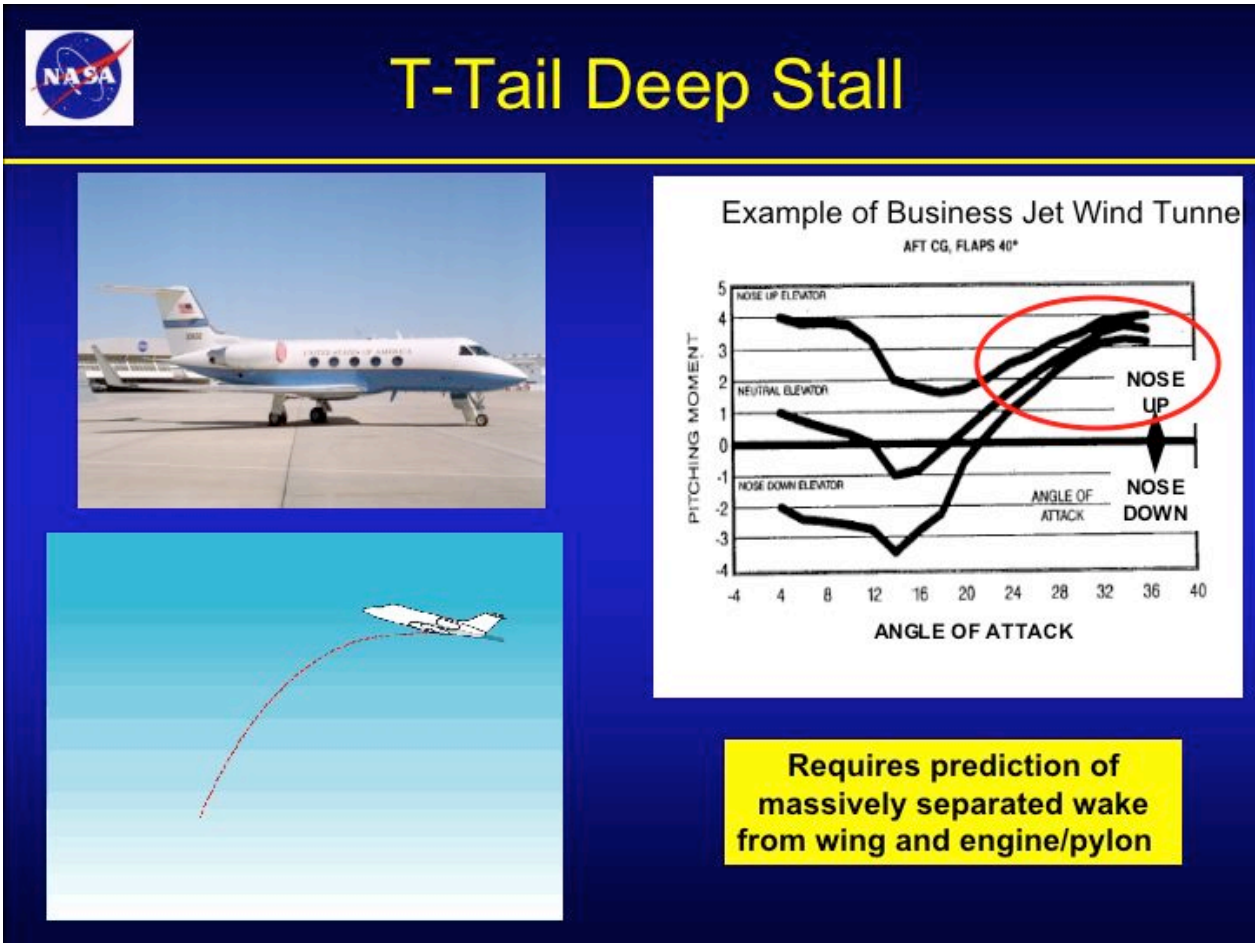
Video of F-4 experiencing directional departure during flight-test wind up turn and entering flat spin illustrates how rapidly the airplane goes from controlled to uncontrolled flight.



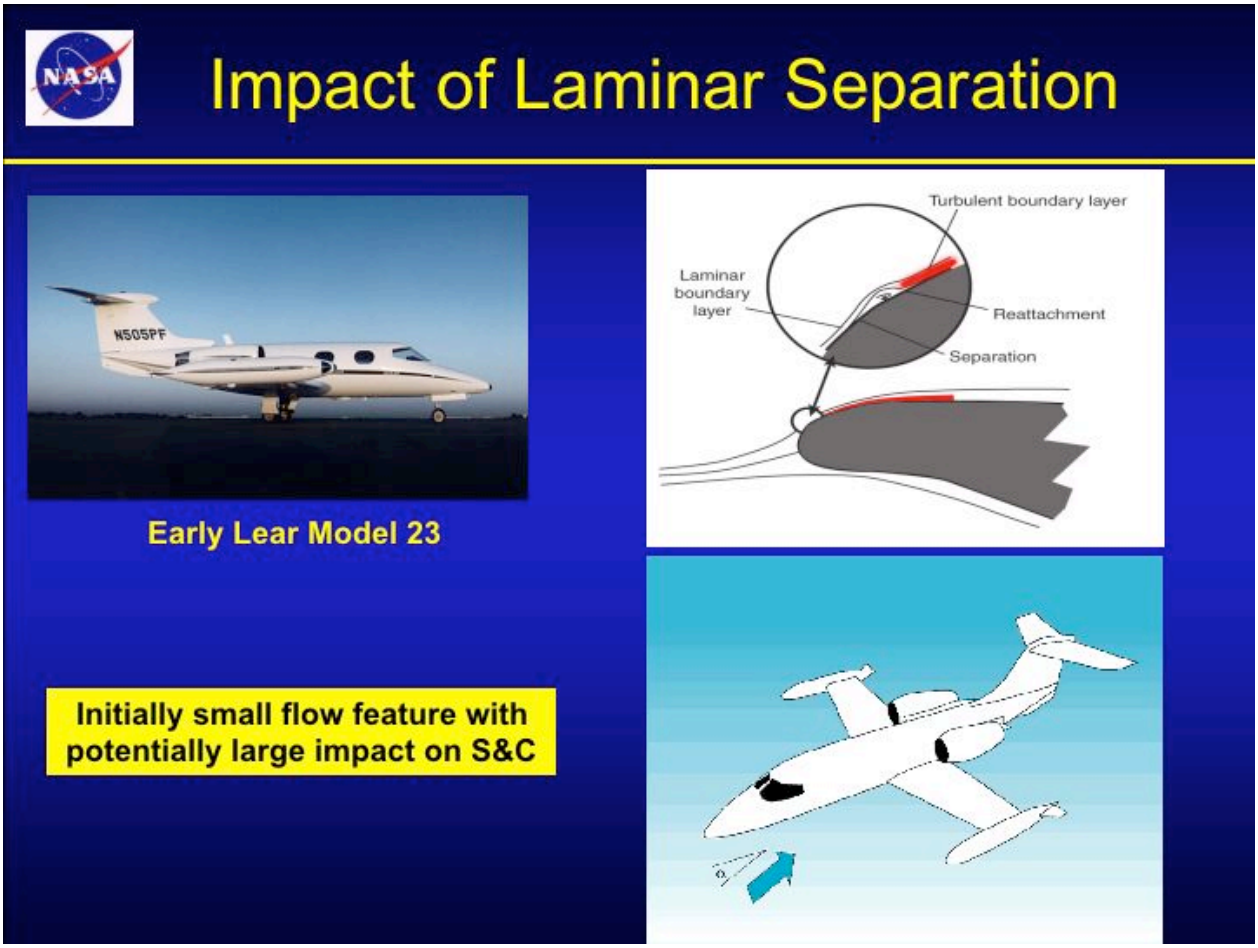
Again, many S&C issues in common with large transports and high-performance fighters, but business jets tend to have T-tails and commonly do not have leading edge devices, potentially leading to issues with deep stall and laminar separation bubbles, respectively.



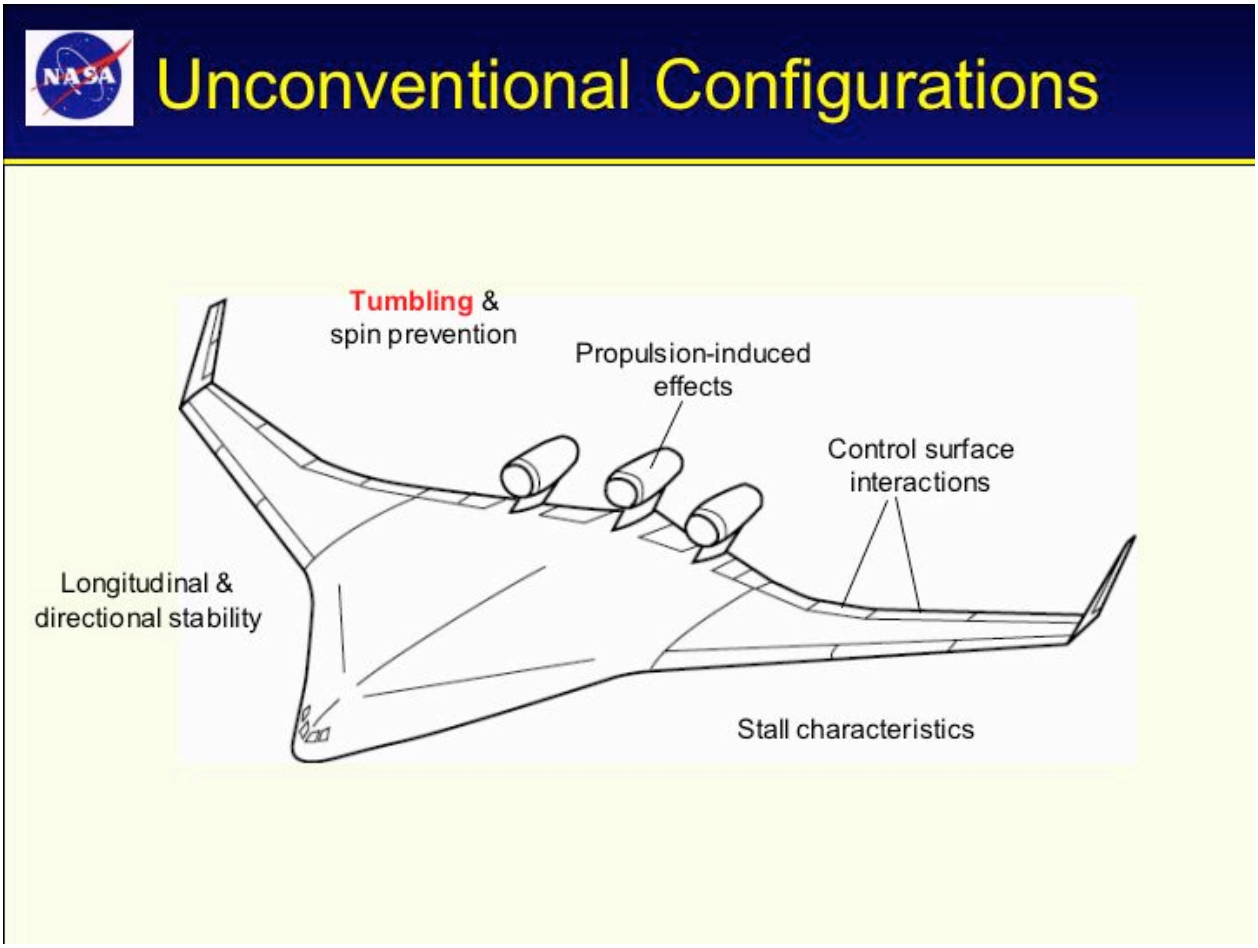
Wind tunnel data (NOT for configuration in photo at left) show that some T-tail airplanes do not have enough nose-down control authority at high angles of attack to recover from a deep stall.



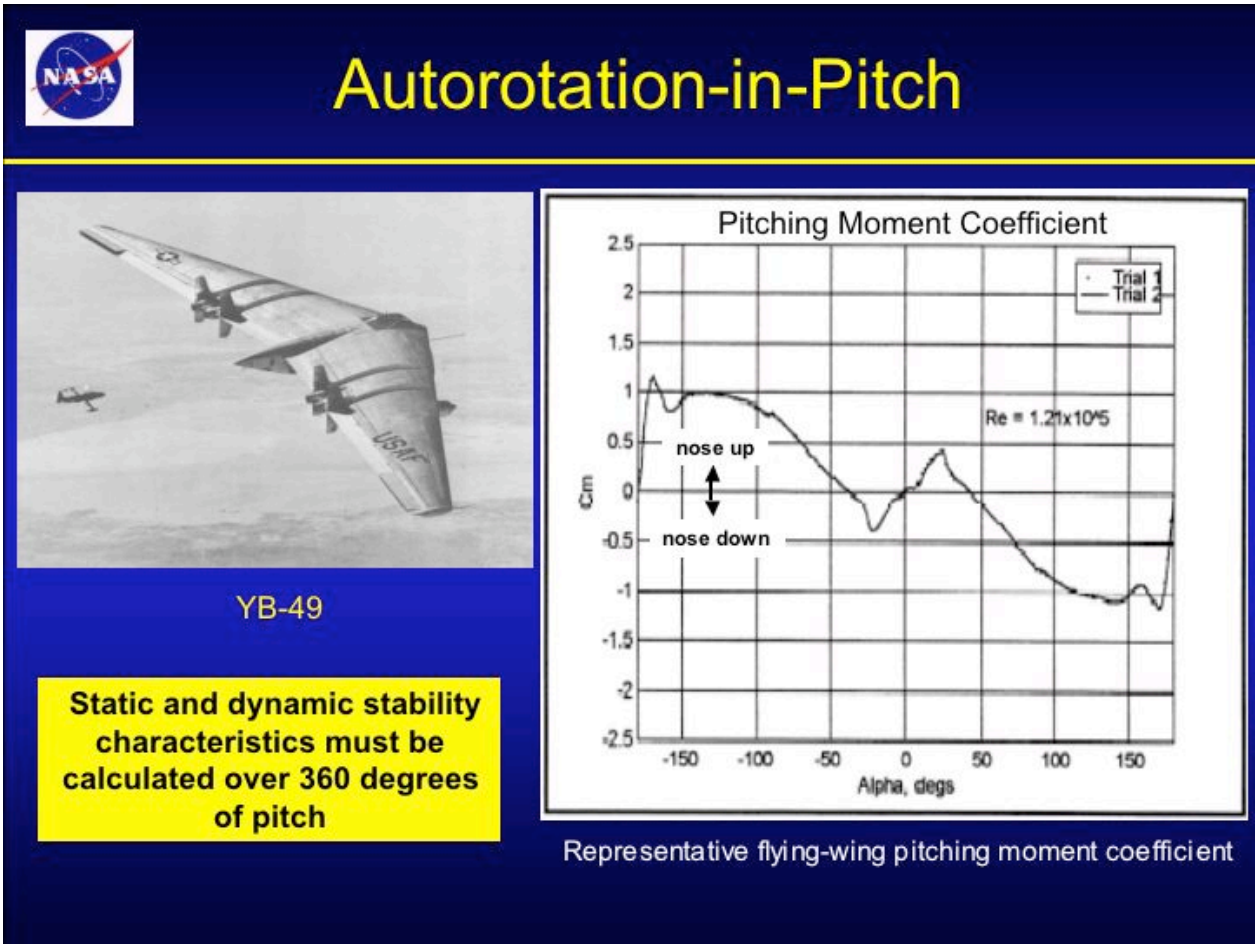
Animation shows laminar separation "bubble" at leading edge at elevated angle of attack (e.g. in landing configuration) progressing to sudden full wing stall on one side after the bubble "lets go" and the entire surface separates abruptly. Large rolling moments are then induced by the asymmetric stall pattern, which is potentially catastrophic if the airplane is at low altitude.



Unconventional configurations such as flying wings are illustrated by the Blended Wing Body (BWB). Flying wings have many distinct S&C characteristics, depending on the geometry, but may include reduced longitudinal and directional stability due to the lack of a tail, highly non-linear control surface interactions if there are multiple control surfaces, and the potential for entering a tumble mode (i.e., autorotation in pitch).



The Northrop YB-49 (and earlier XB-35) were advanced all-wing bombers produced in the late 1940s. Longitudinal stability in general (and tumbling in particular) were identified as potential problems for flying wings early on, and experimental studies were conducted to identify potential problem areas. The plot shows wind tunnel pitching moment data for another flying wing which shows that the vehicle is statically unstable in pitch (I.e., the slope of the curve is positive near zero angle of attack), which could lead to a pitch departure if the dynamic pitch damping is such that rotation is sustained over a complete 360 degree cycle.



Autorotation-in-Pitch

Generic flying wing in LaRC Vertical Spin Tunnel

Recommendations

- Focus on mix of near-term and far-term objectives
  - Combination of component studies and complete configurations
- Collate and assess knowledge of major flow phenomena (stall progression, hysteresis, etc.) to prioritize work
- Critically address the level of code required for specific issues
  - Design, high-fidelity assessments, database, etc.
- Define S&C experimental measurements required for calibration of codes
  - Rn, M, flow physics diagnostics, rigs, testbeds, etc.

S&C community must answer for CFD community:

"How good is good enough?"

Concluding Remarks

- The challenge of predicting aero S&C parameters using CFD is formidable
- The potential payoffs are unprecedented
- Massive amounts of experimental data are available for general guidance
- Very few S&C experiments have been designed for code calibration
- COMSAC must be a close collaboration of the S&C and CFD communities from industry, government, and academia on a national level

Emerging CFD Capabilities and Outlook – A NASA-Langley Perspective

Robert T. Biedron, S. Paul Pao, and James L. Thomas
NASA Langley Research Center

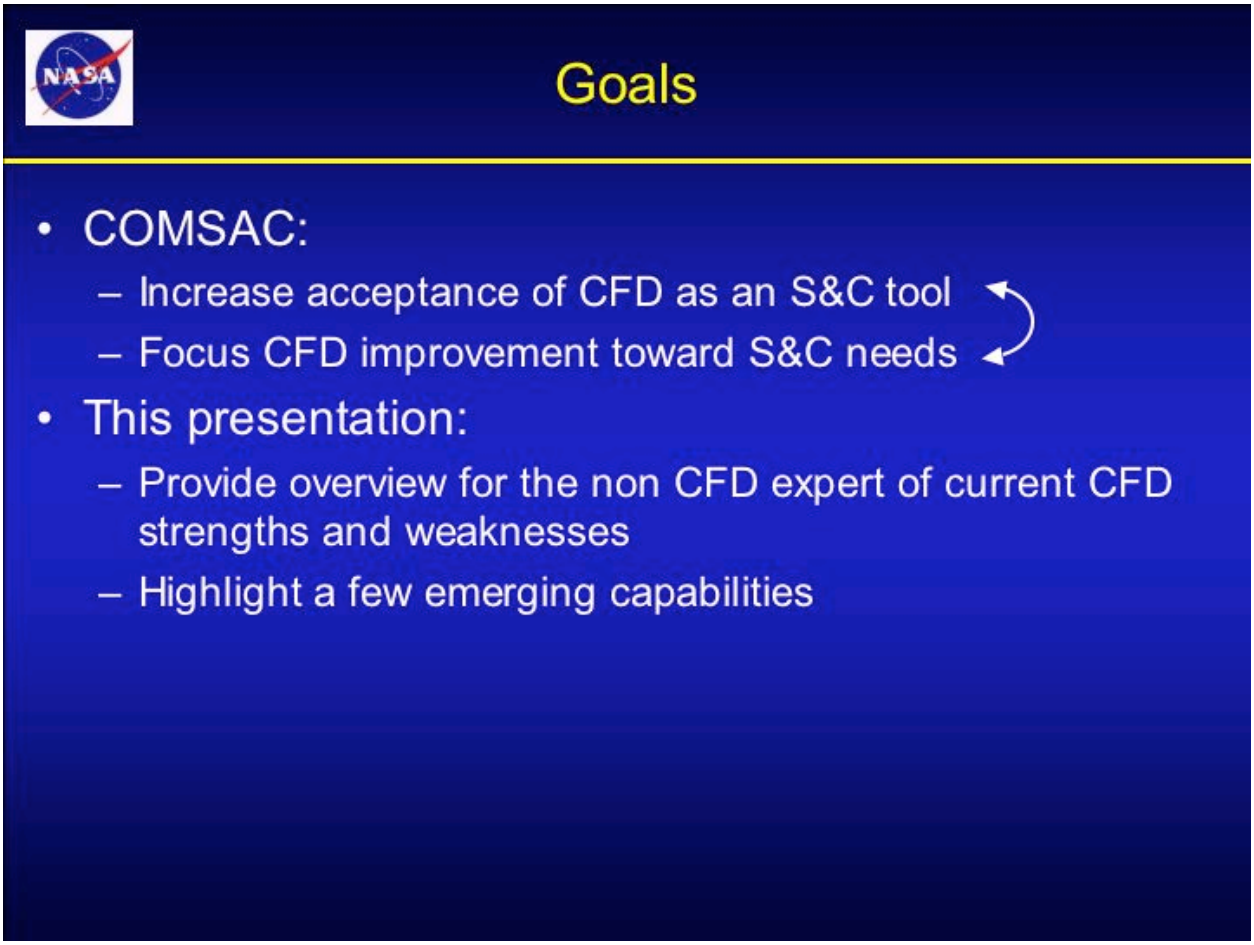
COMSAC Symposium
September 23, 2003

Outline

- Goals
- Preliminary Material
  - Equations and Modeling
  - Grid Types
  - Solution Process Today
- Sampling of Current Capabilities
- Applications of CFD to F/A-18 S&C
- Important CFD Issues for S&C
- Technology Barriers
- Emerging Capabilities
- Outlook

COMSAC goals include increasing the acceptance of CFD as a viable tool for S&C predictions, as well as to focus CFD development and improvement towards the needs of the S&C community. We view this as a symbiotic relationship, with increasing improvement of CFD promoting increasing acceptance by the S&C community, and increasing acceptance spurring further improvements.

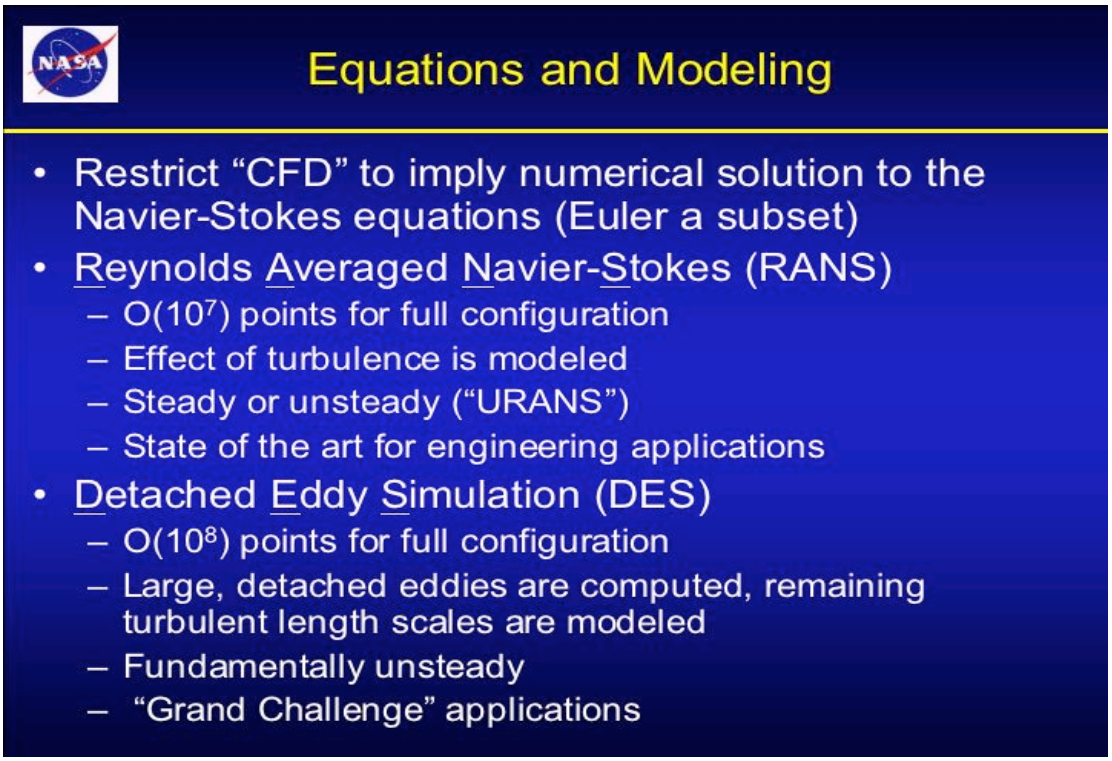
In this presentation we want to provide an overview for the non CFD expert of current CFD strengths and weaknesses, as well as to highlight a few emerging capabilities that we feel will lead toward increased usefulness in S&C applications.



"CFD" can imply different things to different people. To put everyone on the same footing for this presentation we are going to restrict the definition of CFD to imply the numerical solution of the Navier-Stokes equations, with the Euler equations as a subset.

There are of course many levels of approximation to the Navier-Stokes equations, principally distinguished by how turbulence is treated. In principle one can use a fine enough mesh and a small enough time step to resolve and track all the important scales of the turbulence. Such solutions for full aircraft geometries are many decades away. So for practical applications we must resort to some level of turbulence modeling.

At the highest level of turbulence modeling lie the Reynolds Averaged Navier-Stokes (RANS) solvers. These solvers require $O(10^7)$ points for a complete configuration in order to have an adequate resolution of the flow field. In a RANS code, the effect of turbulence is entirely



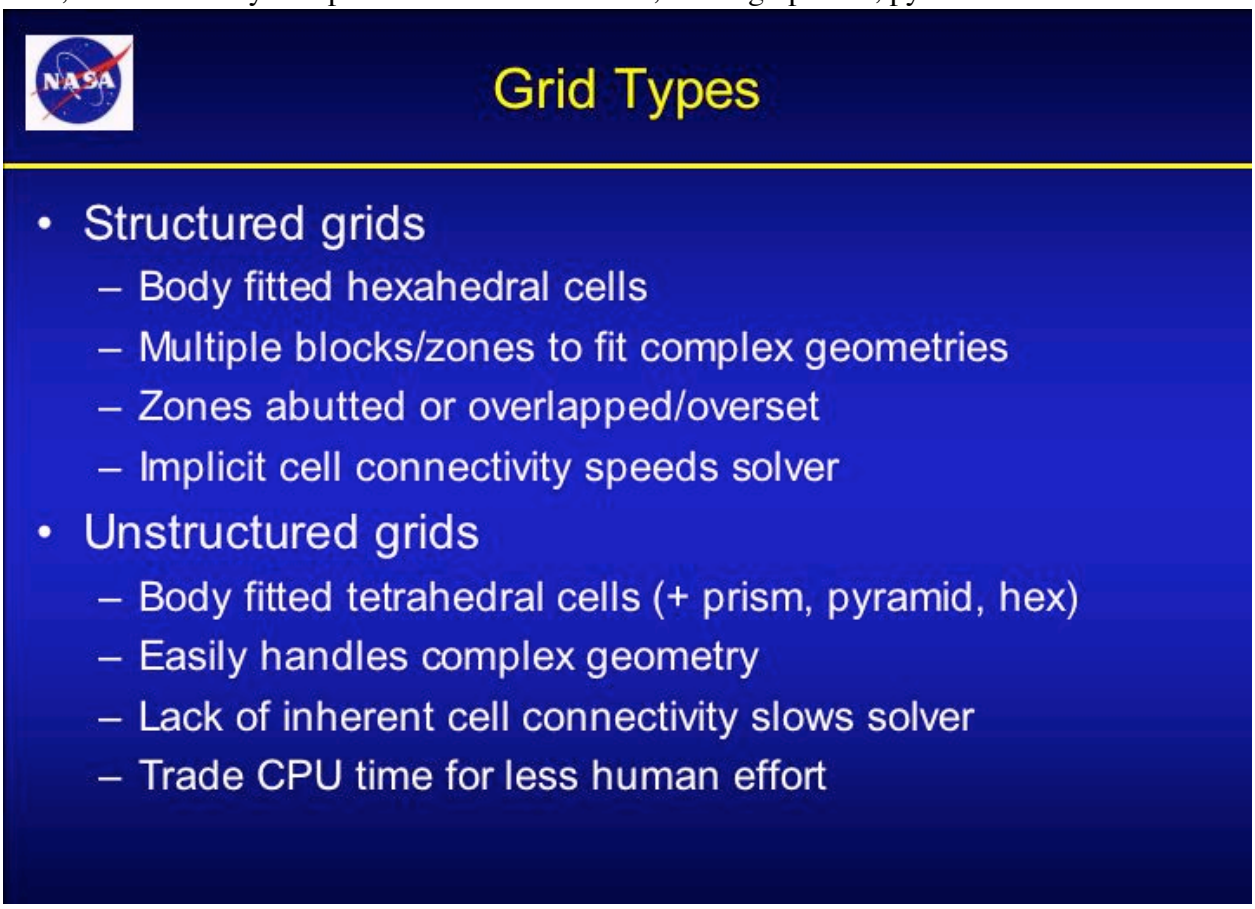
modeled; the grid is not dense enough to realistically track individual turbulent eddies anywhere in the field. Many RANS codes can simulate both steady and unsteady flows; those that simulate unsteady flows are often referred to as URANS. One might label RANS solvers as "state-of-the-art" for engineering applications.

RANS codes tend to do a poor job with massively separated flows. Detached Eddy Simulation (DES) is one of a number of hybrid methods that have been proposed to better deal with these flows. A well-resolved DES calculation may require $O(10^8)$ points. Large, detached eddies in the separated flow region are computed and tracked, while the remaining turbulent length scales (near the body) are modeled with the RANS approach. A DES simulation is fundamentally unsteady. The need for very large numbers of grid points and time-accurate simulation puts DES out of the engineering realm at this time, into the "Grand Challenge" category.

All CFD codes employ some sort of grid or mesh, and may be categorized into two general types by the kind of grid used.

Structured grids are comprised of body-fitted hexahedral cells. In order to fit around complex geometries, structured grids must usually be made up of multiple blocks or zones of points. These zones may either abut against one another, or may overlap. Overlapped grids are often referred to as overset grids. Flow solvers utilizing structured grids make use of the inherent connectivity (or structure) between the cells, resulting in relatively fast flow solvers.

The other major category of flow solvers utilize unstructured grids. Such grids are also body fitted, but are usually comprised of tetrahedral cells, although prisms, pyramids and hexahedra

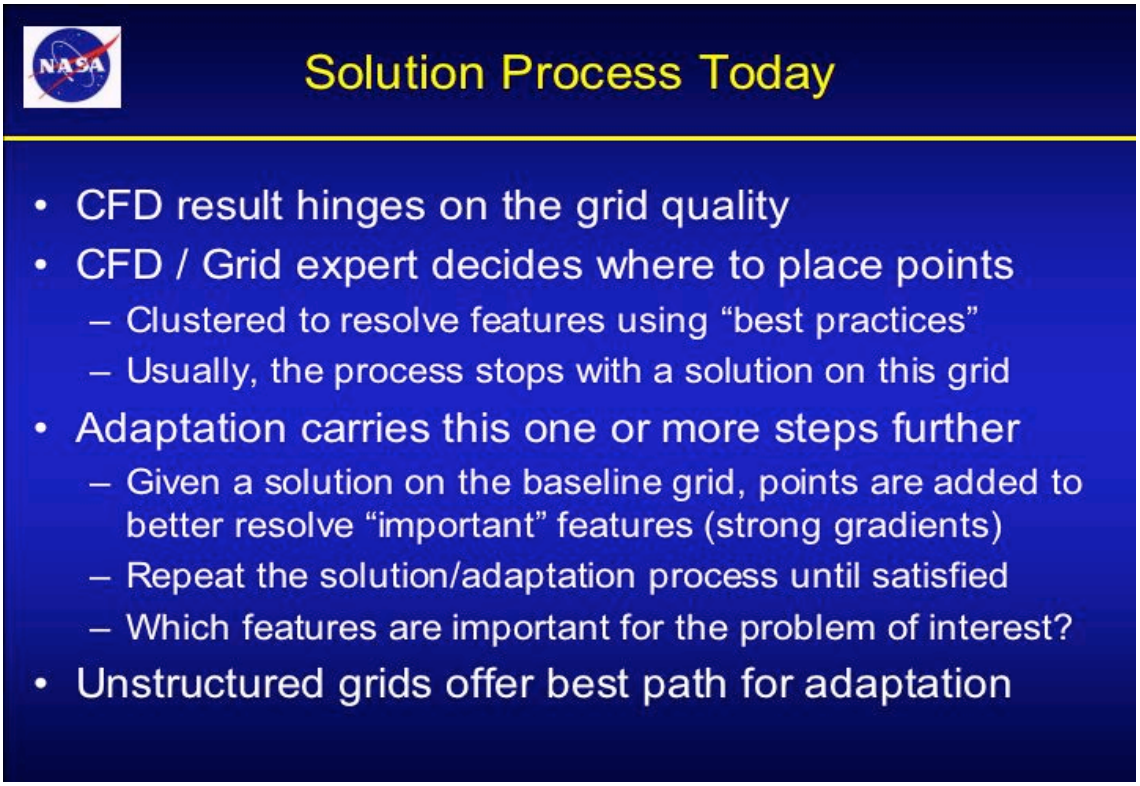


are often used. Prisms are particularly well suited for use within the boundary layer. Unstructured grids can readily handle complex geometry, easing the grid generation problem. The lack of any inherent connectivity between cells means that nearby neighbors of each cell must be explicitly spelled out for the solver, resulting in a slower speed than a comparable structured-grid solver. However, the ease of grid generation, as well as the relative ease of adaptation, discussed in subsequent slides, makes unstructured solvers very attractive – it's a tradeoff of more CPU time for less human effort.

To set the stage for later discussion it is worthwhile to give a very broad overview of the CFD solution process in today's environment. First, it is important to emphasize that the quality of a CFD result hinges on the quality of the grid.

When generating the grid (typically a substantial undertaking), the CFD expert or grid expert (ideally one person expert in both areas) decides where to place points. Typically points are clustered to resolve geometrical features and flow features using established "best practices". After the grid is generated, the flow solver is run and the process stops with a solution on this grid.

Adaptation carries the process one or more steps further. Given a solution on the baseline grid, obtained as described above, points are added to better resolve "important" features, typically

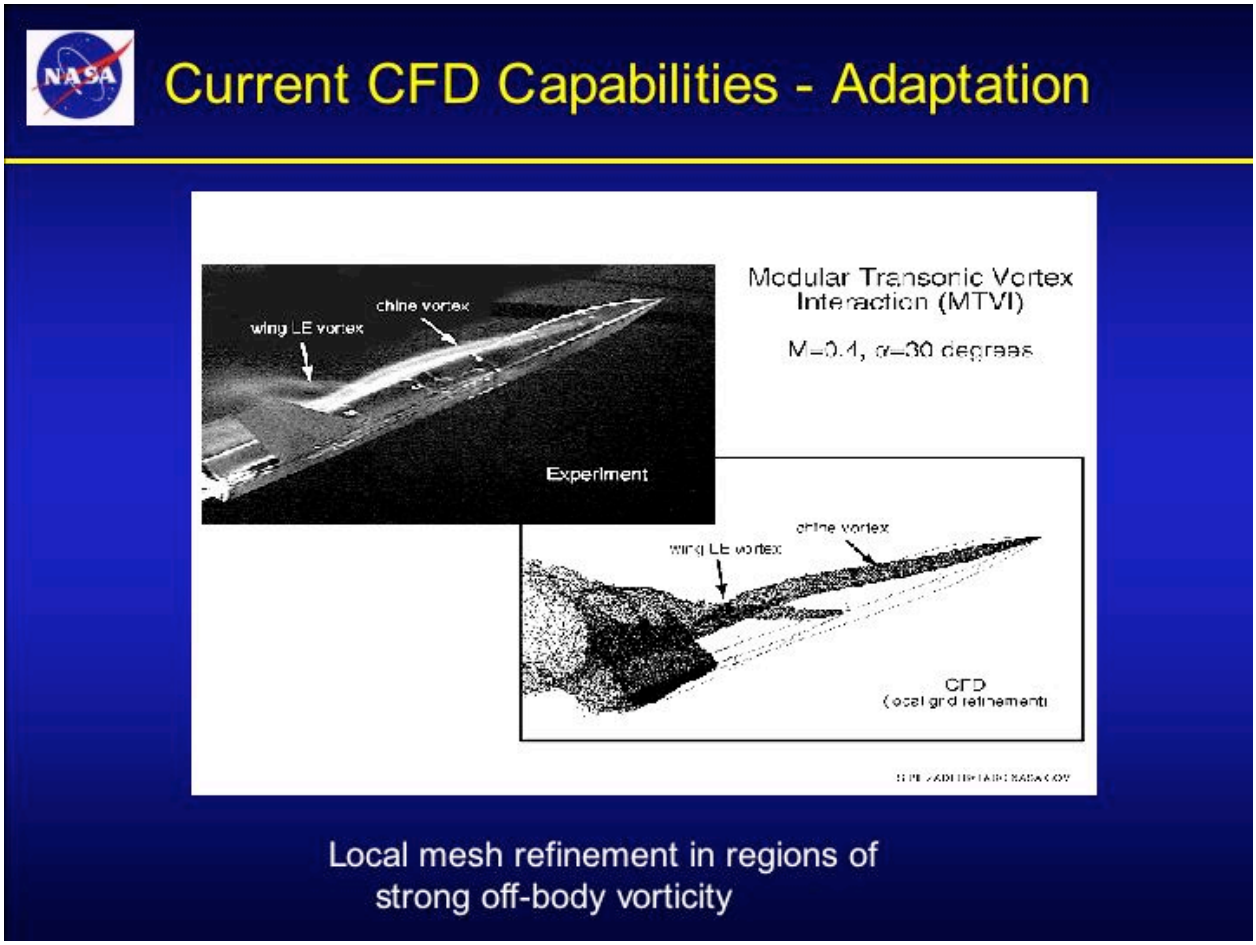


indicated by regions of strong gradients. Then the solution/adaptation process is repeated until the user is satisfied (or gives up…). A fundamental question, sometimes not easily answered even by the expert, is what features and regions are important to resolve in order to get the desired results for the problem of interest?

Adaptation may be done in with formal process as described above. More often however, there is a less formal approach to "adaptation" that occurs when the original grid fails to produce the desired result. In these cases the grid is changed in a manner deemed to result in a better CFD prediction from subsequent simulations. Unstructured grids offer the best path for adaptation as points can more easily be inserted into the grid as needed.

This slide and the next are intended to give an overview of some of the current capabilities of CFD.

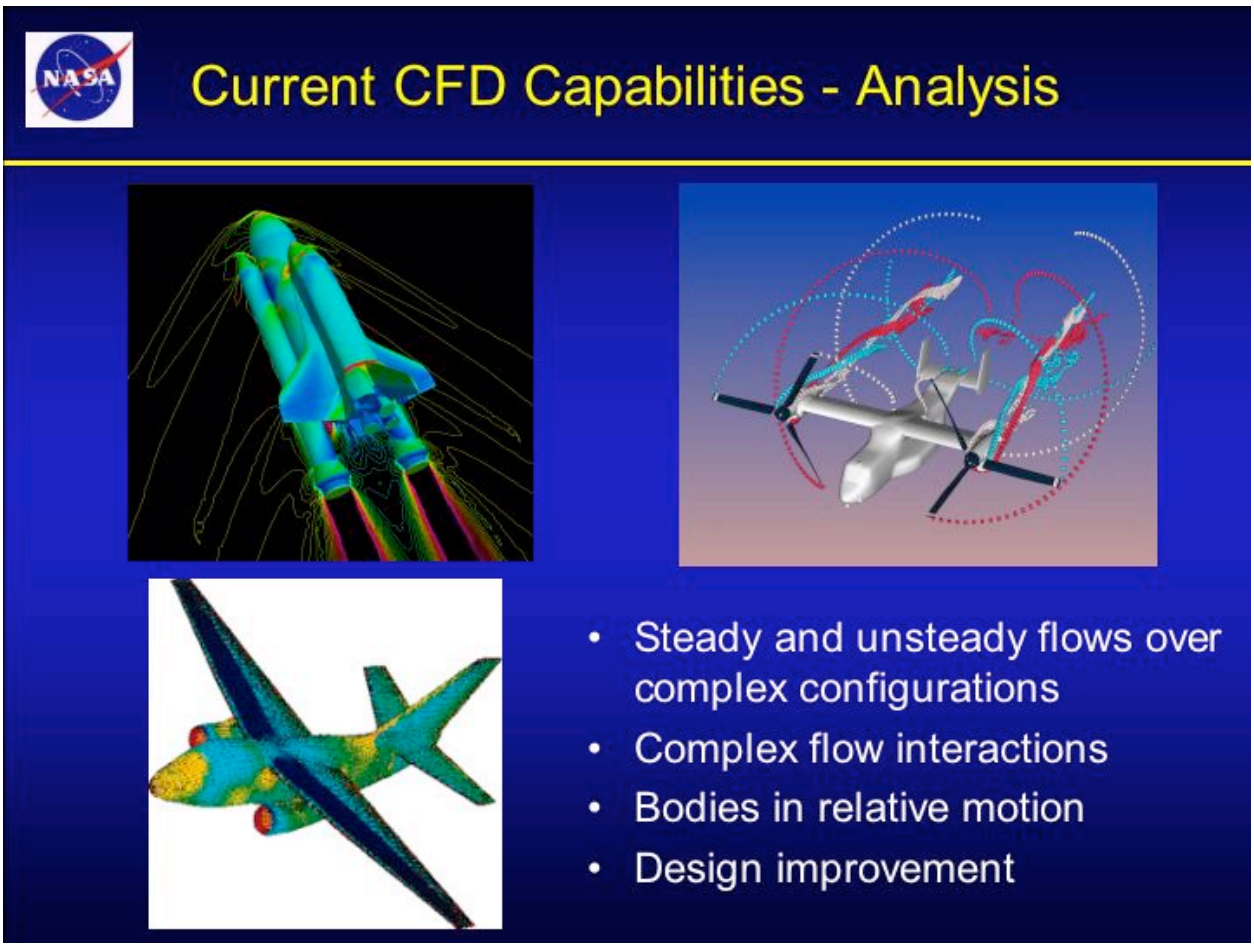
Here we show a solution-adapted grid for a Modular Transonic Vortex Interaction (MTVI) configuration. This modular wind-tunnel model was used to provide detailed experimental data for CFD validation with a wide variety of vortical flows. The image in the lower right shows the grid in the vortical flow regions after refinement. The refinement was based on the locations of strong off-body vorticity as computed by the flow solver. The chine and wing leading edge vortices are indicated. The image in the upper left shows the corresponding flow visualization from the experiment. In this case the adaptation process was critical to the prediction of vortex bursting, which in turn was critical to predicting pitch up.



This slide shows a sampling of the wide range of problems that have been tackled using CFD.

Today's CFD codes are capable of simulating a wide variety of steady and unsteady flows over complex configurations. An example of a steady flow simulation is that shown for the S3 Viking in the lower left.

Complex flow interactions may arise even for simple geometries, but are the norm for complex configurations. An example is the full-stack Space Shuttle simulation in the upper left. Here we see the multiple shock waves formed during ascent.

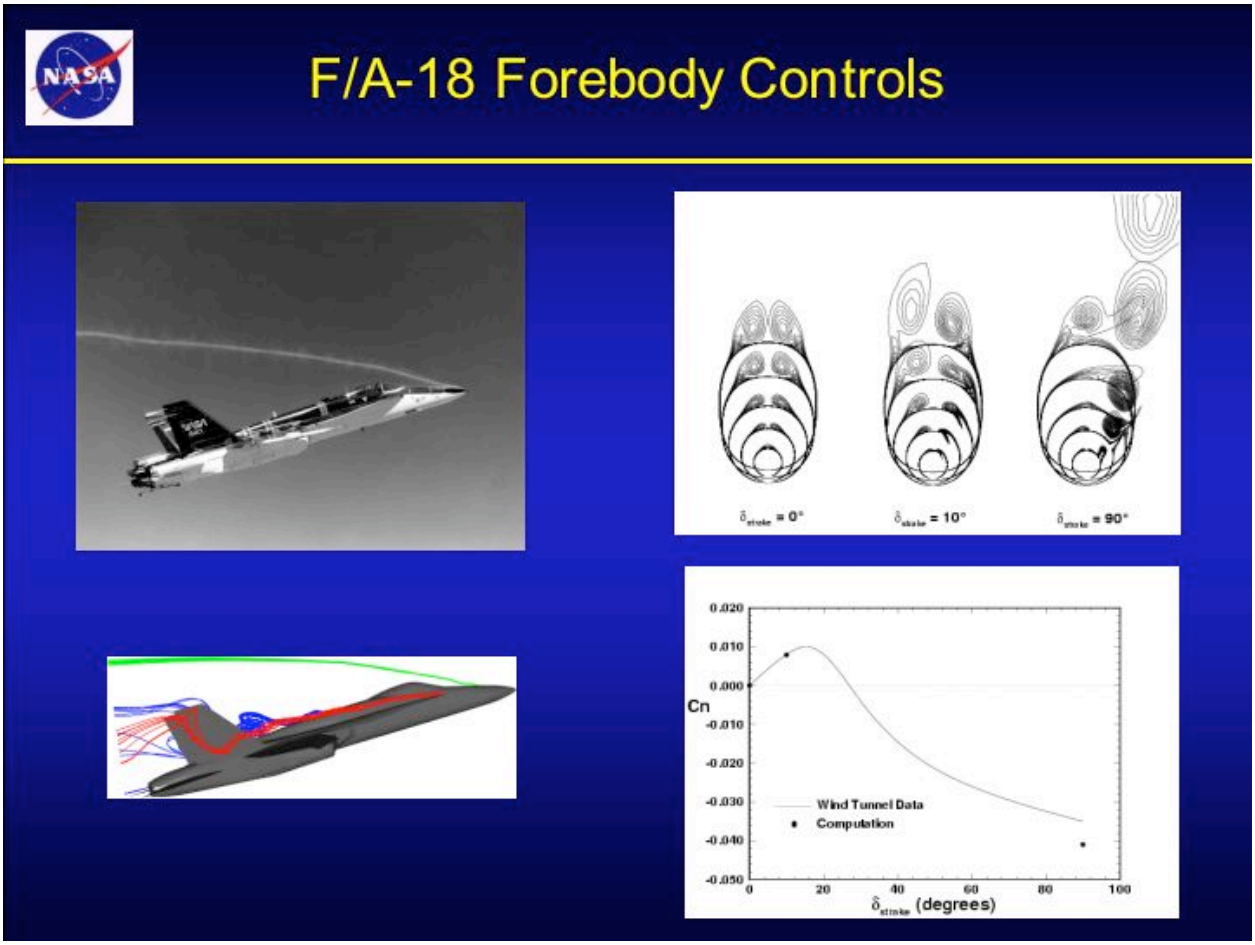


Unsteady simulations may include bodies in relative motion. In the upper right is shown a computation of the V22 Tilt Rotor with the spinning blades in the cruise mode. The complex wake structure is made visible by particle traces emanating from the rotors and wing tips.

Although not shown, analysis capabilities have been extended into the design environment in limited applications. More precisely, the use of CFD in design has been largely limited to design improvement, rather than for conceptual design. However, efforts are underway to bring CFD earlier into the design process.

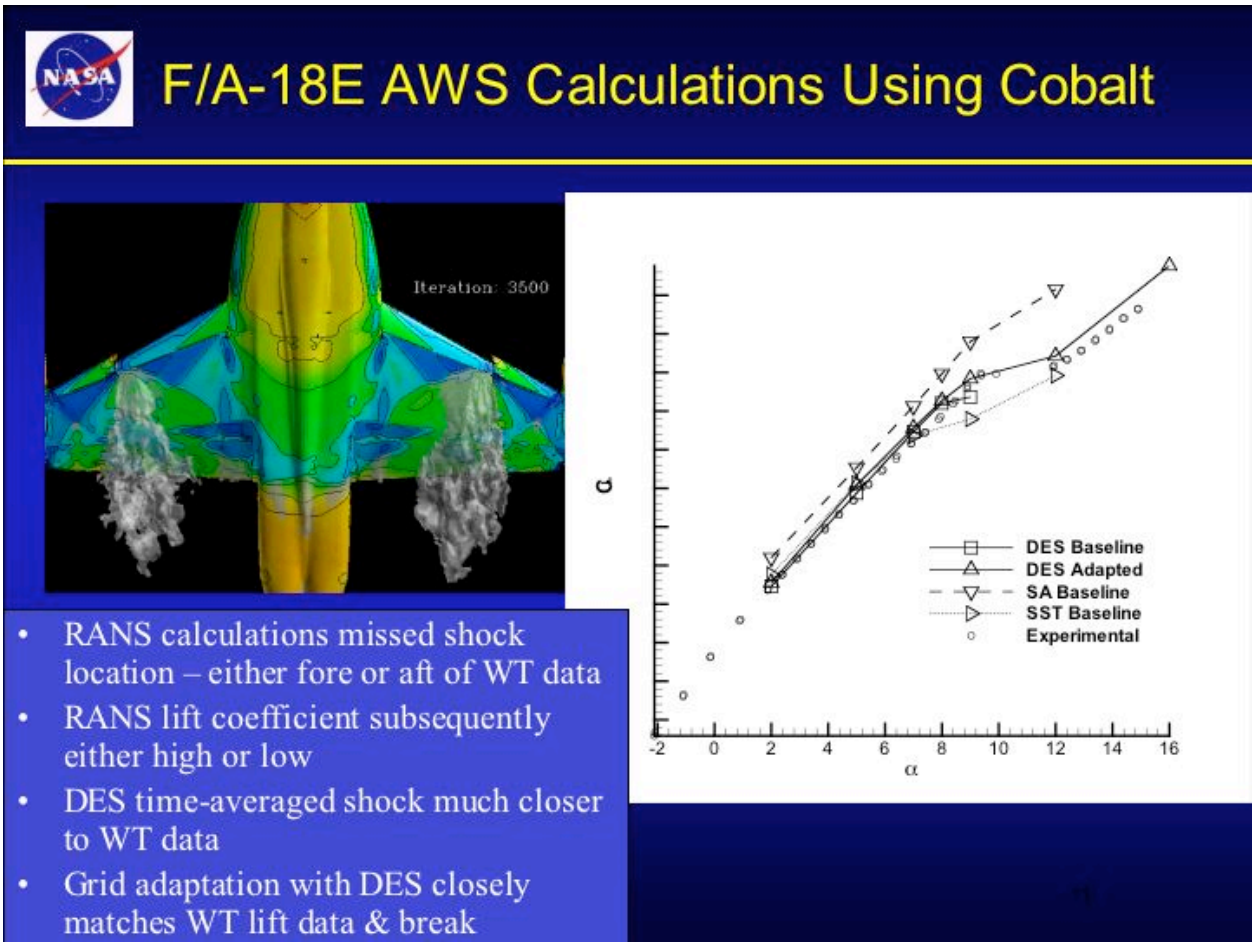
Now let's look at two applications of CFD to stability and control of the F/A 18 aircraft, in the areas of Forebody Controls and Abrupt Wing Stall.

In the High Alpha Technology Program, a number of novel control effectors for maneuvering at high angles of attack were studied. Among them was an actuated nose strake, designed to be deployed on an as-needed basis. Early on in the wind tunnel program, using a generic strake design, it was observed that the direction of the yawing moment produced by the strake changed with deployment angle. CFD was used to confirm the experimental observation for the final strake design intended for use on the aircraft. The image on the top right shows (left to right) the vortical structure with the strake retracted, extended 10 degrees, and 90 degrees (full extension). The image on the lower right shows the computed yawing moments (symbols) for those three strake positions, as well as the wind tunnel measurements for a range of deflections (line). It is seen that CFD simulation has correctly predicted the yawing moment reversal, and has done a reasonable job at predicting the magnitude of the yawing moment.



The image in the top left shows in-flight visualization of the vortex generated by the nose strake (fully deployed); the image in the lower left shows the corresponding visualization from the computation (green trace). Also shown are the traces of the LEX vortices (red and blue traces); the asymmetrical LEX vortex breakdown induced by the nose strake deployment is evident.

This slide shows a more recent application, by Jim Forsythe using the Cobalt code, for the prediction of Abrupt Wing Stall on the F/A-18E. The "E" variant exhibited an abrupt wing drop for a certain range of Mach number and angle of attack. Initial attempts using the RANS approach with either the Spalart-Allmaras (SA) model or the Shear Stress Transport (SST) model missed the shock location and thus gave incorrect predictions for the lift coefficient. In the case of the SA model the lift coefficients were in general too large, and though the break in the lift curve slope was correctly predicted near nine degrees angle of attack, the reduction in slope was under predicted. Conversely, using the SST model, the lift coefficients in the attached flow region were well predicted, but the break was predicted to occur too soon.

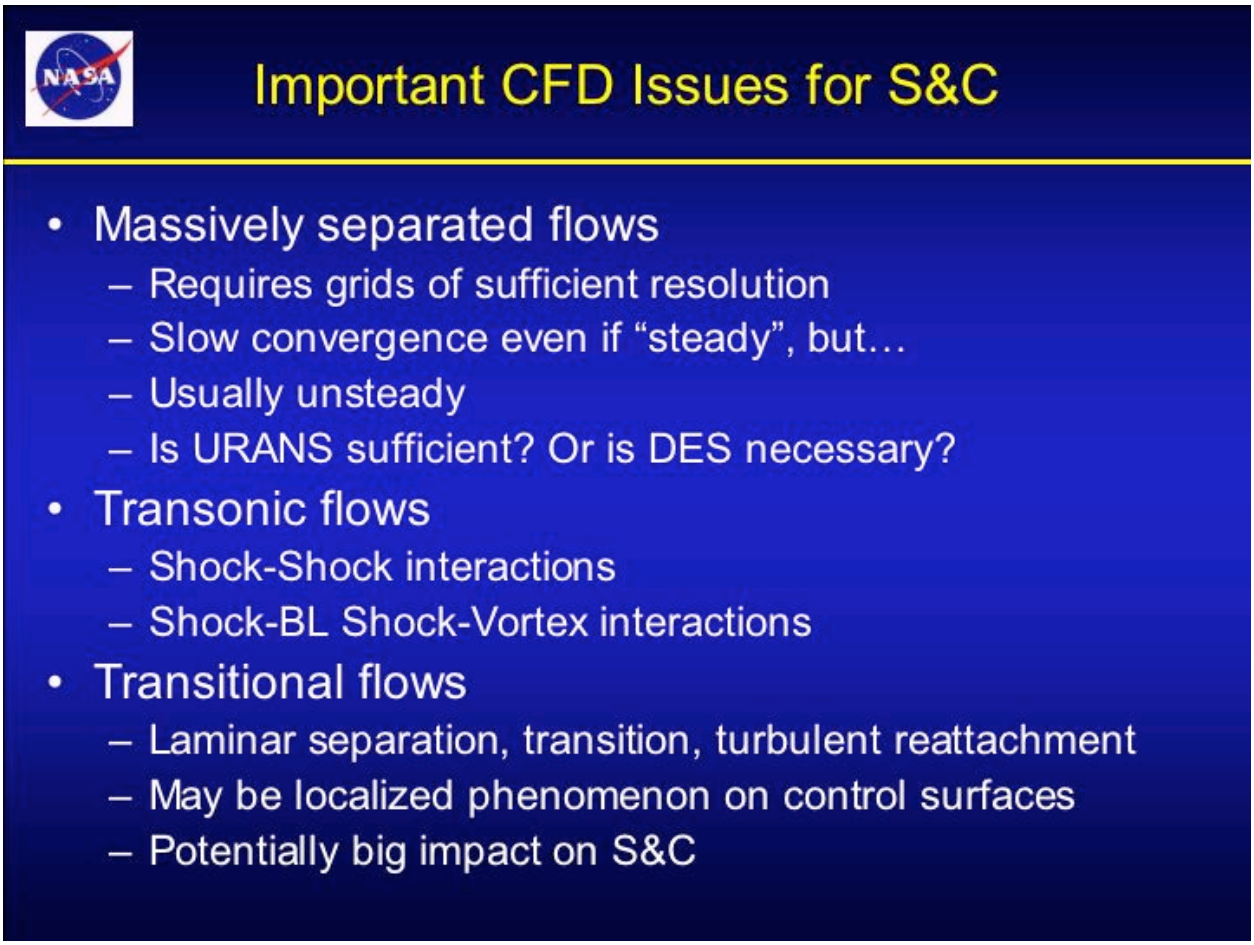


Subsequently, the DES approach was employed, using the SA model near the body. Time averaged output showed a more accurate prediction of the shock location compared to the standard RANS model with SA. Improvement was also seen in the lift coefficient near the break, but the break occurred too early. Finally, the grid was solution-adapted to the initial DES result, and the DES solutions were re-run. Time averaged lift coefficients from the DES simulations showed excellent agreement with the data, predicting the break near nine degrees correctly, as well as the correct reduction in slope, and the subsequent increase in lift curve slope beyond 12 degrees.

Now that we have shown a sampling of CFD capabilities, including some directly addressing S&C, lets consider some important CFD issues that can directly impact S&C calculations.

Massively separated flows will be quite common for S&C applications. Such flows require a grid of high resolution to adequately capture the slow-moving wake regions, which tends to slow the convergence of the CFD solution even for nominally steady flows. But in reality such flows are usually unsteady and we may need to do time dependant simulations in order to properly capture the relevant effects.

Then the question arises, is URANS sufficient or do we need DES? The preceding slide gave evidence that the DES is required in at least some situations. This leads to greater computational cost.



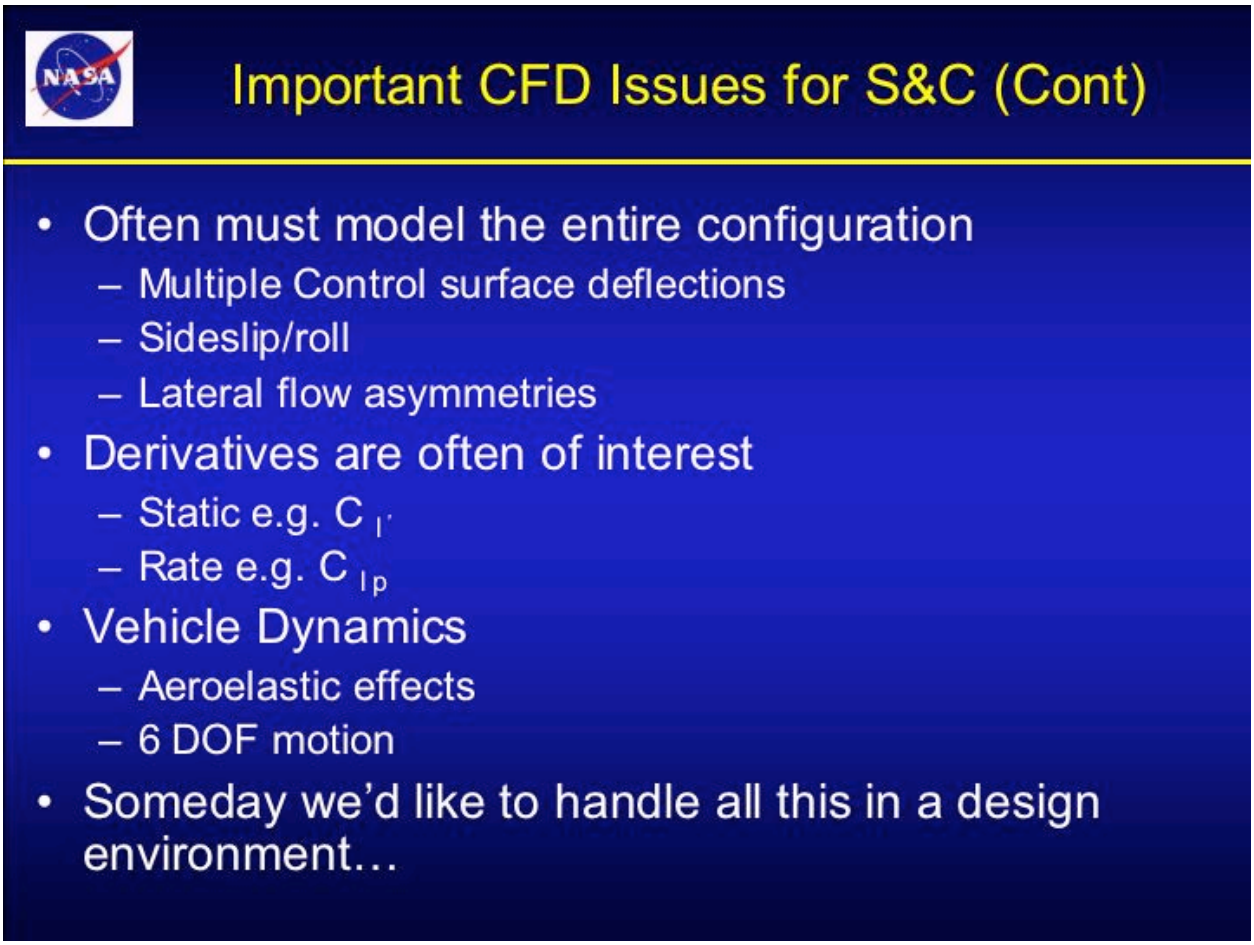
In many cases we will be dealing with transonic flows, and so we may need to resolve complex flows involving shock-shock interactions, shock-boundary layer interactions, and shock-vortex interactions.

Another potentially large issue involves transitional flows, especially ones involving laminar separation, transition to turbulent flow, and subsequent reattachment. Physics-based prediction of transition is not generally available in Navier-Stokes solvers. Even for high Reynolds Number flows based on vehicle length scales, there may be localized transitional phenomenon on control surfaces or near wing leading edges that can have a huge impact on S&C.

We will often have to model the entire configuration. This of course requires double the number of grid points needed compared to situations where symmetry can be assumed.

Such things as differential control surface deflections, sideslip or roll, as well as lateral flow asymmetries arising in a nominally symmetric configuration will dictate a full grid.

Derivatives are often of interest. Thus we need to be able to calculate these reliably for both static and dynamic situations. It should be noted that often derivatives change sign over very small ranges of flow conditions, so simple finite differencing over (say) angle of attack ranges of a degree or so may not yield sufficient accuracy. Other methods for evaluating derivatives, such as complex arithmetic or differentiated source code can provide more reliable derivatives, but are not available in all solvers.



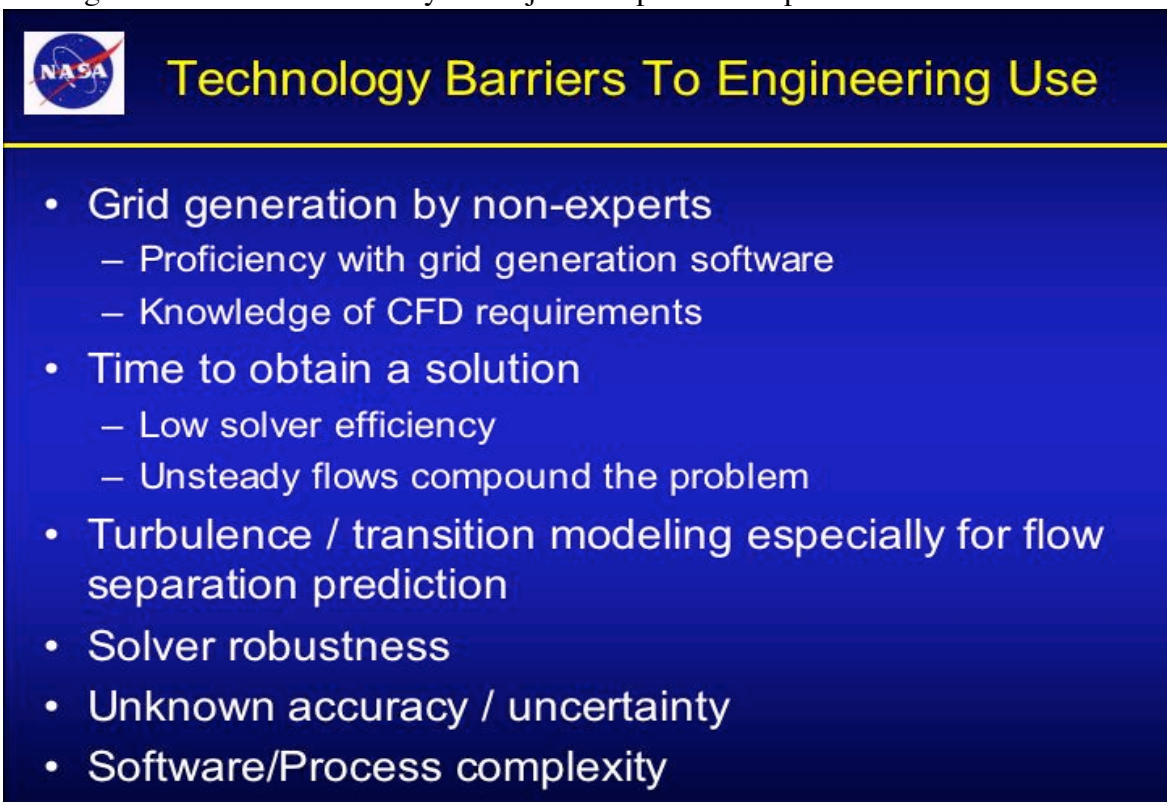
There are many cases where vehicle dynamics are important. These can range from situations in which aeroelastic effects are important to 6 DOF motion.

Finally, at some point many years from now we would like to handle all these situations in a design environment, so that S&C considerations can be designed in from the start.

This slide lists some additional technology barriers that inhibit engineering applications of CFD to S&C.

As things stand today, the whole process of obtaining a CFD solution, but particularly the grid generation aspect, requires a high degree of expertise. This applies to the use of the grid generation software and to the experience required to judiciously place grid points for an accurate CFD result.

The time to obtain a solution is also currently too long for day-to-day engineering calculations. Flow codes are not nearly as efficient at solving the equations as they could be, and the increasing need to simulate unsteady flows just compounds the problem.



The issues of transition and turbulence modeling, especially for separated flows, is one that causes considerable debate even among CFD experts

Solvers are not robust enough. Not every attempt to get a CFD solution is successful, especially at extreme conditions. Even on a good day, if the solver runs 90% of the cases, the remaining 10% seem to require 90% of the user's time.

When a solution is obtained, there may be questions that arise as to it's accuracy, as well as the uncertainty associated with the result. Mike Hemsch will cover these issues in more detail in a separate presentation.

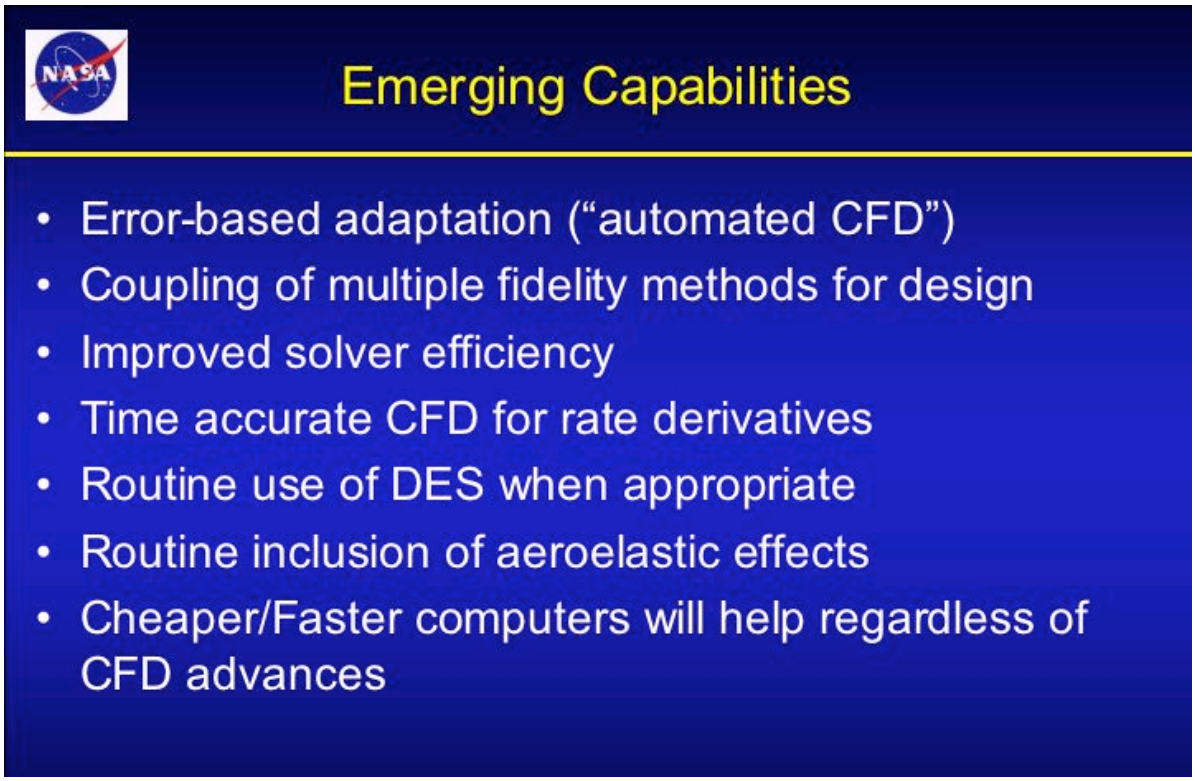
Finally, the whole process is fairly complex, even for the CFD expert, so much work needs to be done to simplify the process for "routine" engineering applications.

Here we list a few capabilities that are emerging and should have a beneficial impact on S&C applications.

The first is error-based adaptation, which should go a long way to automating the CFD process. We will cover this topic in more detail in the next few slides.

There has been some very promising work to couple high-fidelity, Navier-Stokes solvers with lower order, potential or Euler solvers in a design environment. In the long term, this will allow inclusion of CFD earlier in the design process than is currently practical.

A significant effort is underway to increase the basic flow solver efficiencies toward their full potential. This work is particularly targeted towards the multigrid methods. Impressive results



have been obtained for simple flows, but application to complete configurations with complex flows is some years away.

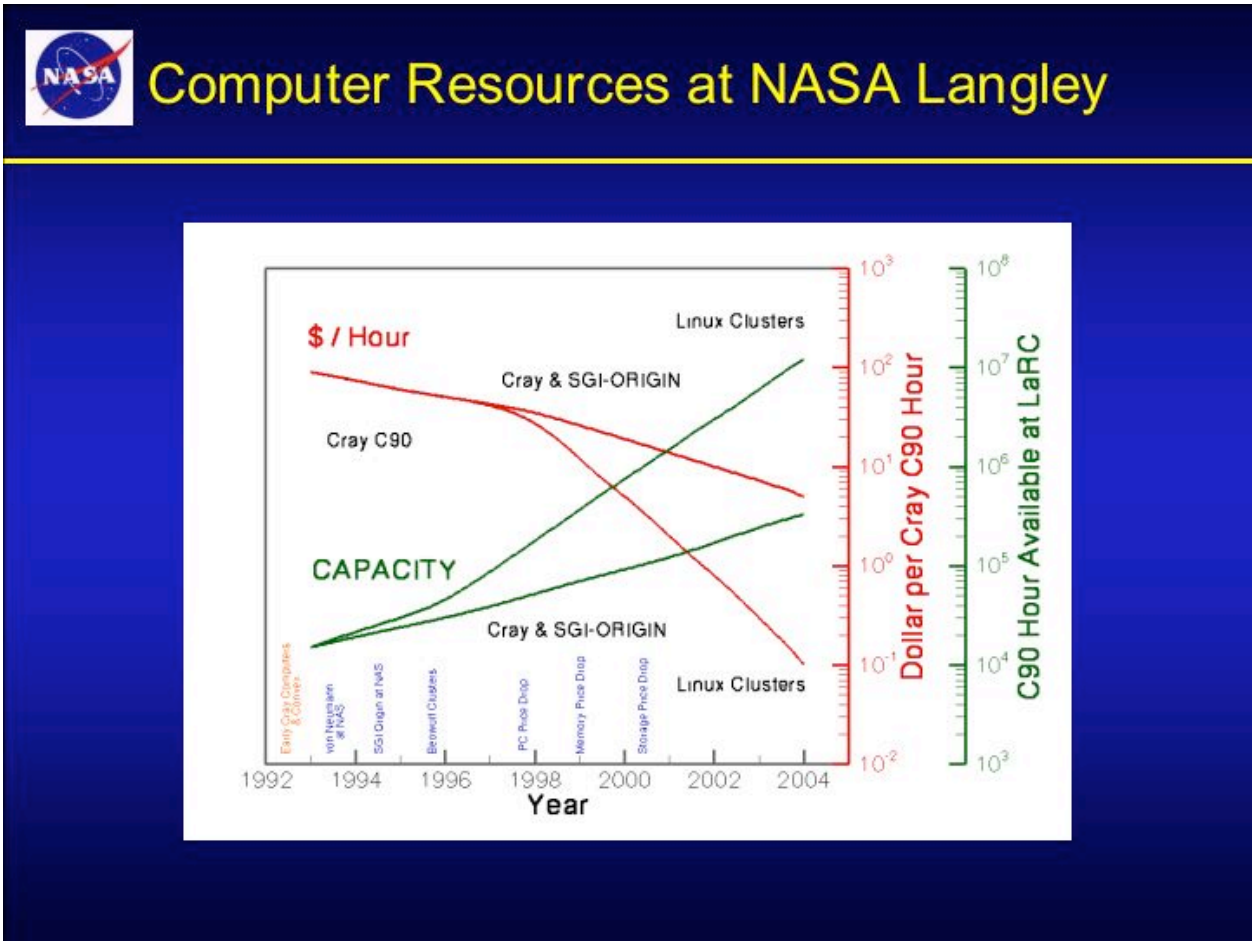
Progress has been made in the computation of unsteady flows, using dual time step methods, as well as the efficient evaluation of rate derivatives for constant rotation rate cases.

The DES method described earlier, has been applied to a wide range of massively separated flows, and may eventually become a routinely used tool for such cases. Likewise, the inclusion of aeroelastic effects, particularly static deformations, is becoming more widely used.

Finally, cheaper faster computers will help bring CFD into the S&C world, regardless of advances on the algorithmic front.

This slide illustrates some trends in computing resources at NASA Langley Research Center – no doubt similar trends can be observed elsewhere.

In the early 1990's we were doing all of out CFD simulations on Cray vector supercomputers. At that time we had approximately 20,000 hours available for the center, and they cost around $100 per hour. By 1995 the SGI Origin class machine was beginning to be widely used, perhaps doubling the available hours and halving the computing costs. Parenthetically it should be noted that a great deal of human effort was required to make the change from the single processor vector machines to the parallel processors of the SGI. Nonetheless, the Origin class machines took over as the primary computing platform by the late 1990's. Both the Cray and the SGI machines were developed with high-end computing as their primary market niche.

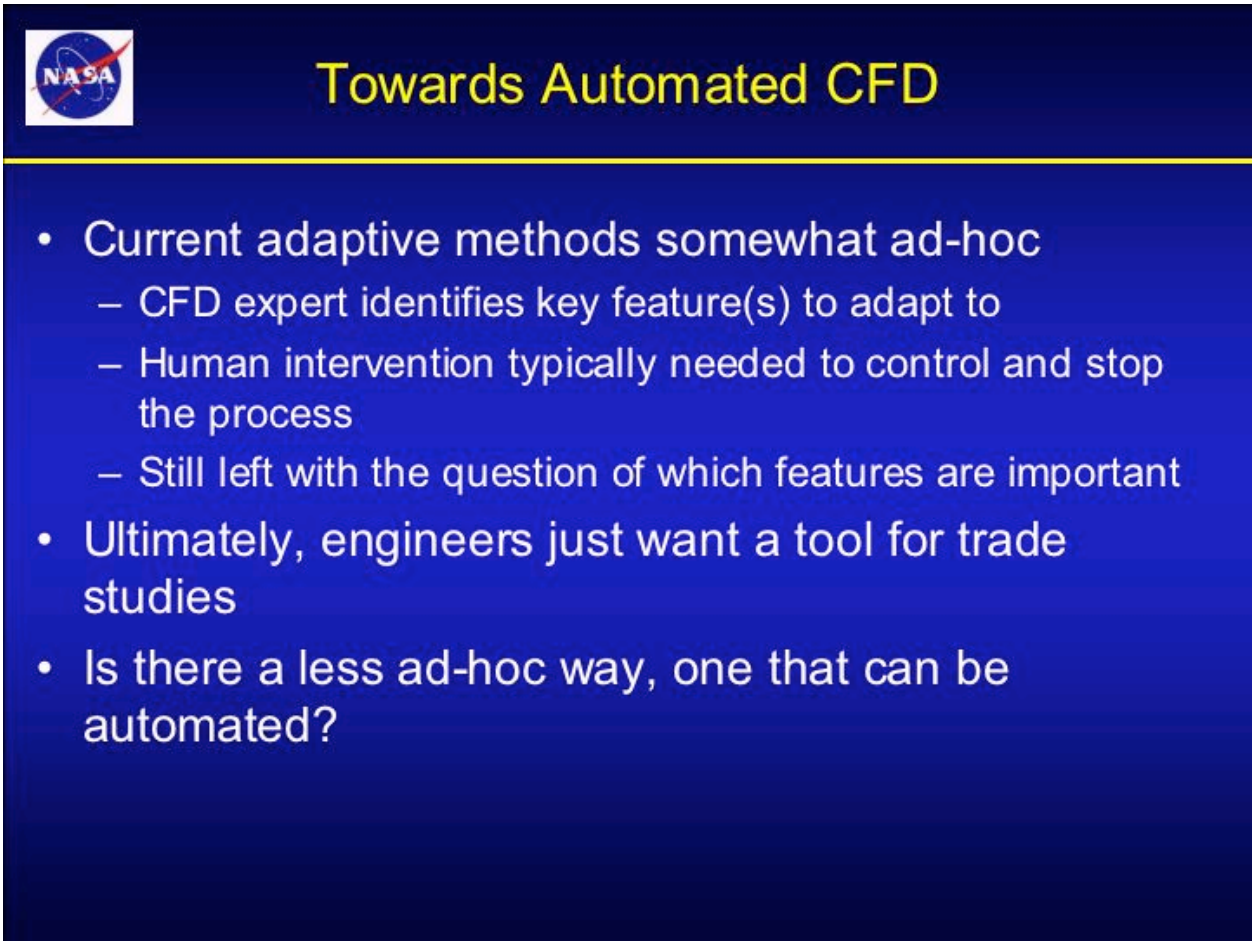


Meanwhile, Linux "Beowulf" clusters of commodity machines appeared, and have been steadily gaining ground. Price drops in CPUs, memory chips and storage have made the Linux clusters very compelling. Having made the effort in converting to parallel processing for the SGI Origin, the effort necessary to adopt the Linux clusters was comparatively minimal. Today there are roughly the equivalent of 10 million Cray C90 hours available, at a cost of about $0.10 per hour.

Now we want to turn attention to a newly emerging technology that shows a tremendous potential as a way to move forward to what might be termed “automated CFD”.

As discussed earlier, current adaptive methods can be somewhat ad-hoc. Recall that the CFD expert must identify the key feature or features to adapt to. Usually, human intervention is required to control the process and decide when to stop. Furthermore, we are still left with the question of what features are important for the problem at hand.

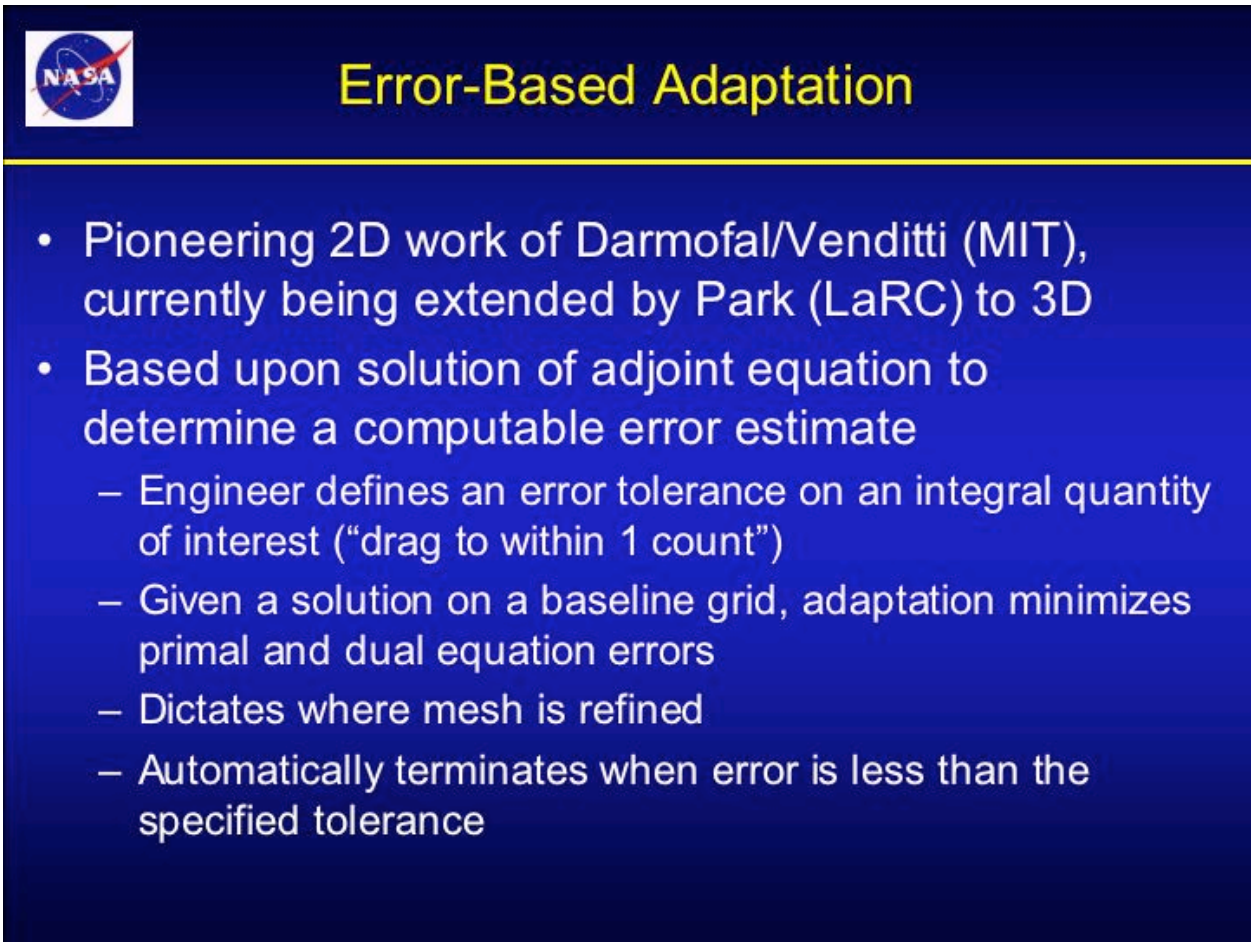
Ultimately, what we want is to provide engineers with a tool that is useful for timely engineering trade studies. So, we must ask, is there a less ad-hoc means of adaptation, and one that can be automated?



Not surprisingly, we believe the answer is "yes" – error-based adaptation.

Error-based adaptation method described here is the result of some pioneering work in two dimensions by Darmofal and Venditti a MIT. It is currently being extended to three dimensions by Mike Park at NASA Langley. As applied to CFD, the method is quite new; though a similar methodology seems to have been used for some time in computational structures.

This methodology is based upon a solution of the adjoint (dual) equations for the Navier-Stokes or Euler (primal) equations, which is used to determine a computable error estimate. In this approach, the engineer defines an error tolerance on an integral quantity of interest. For example,

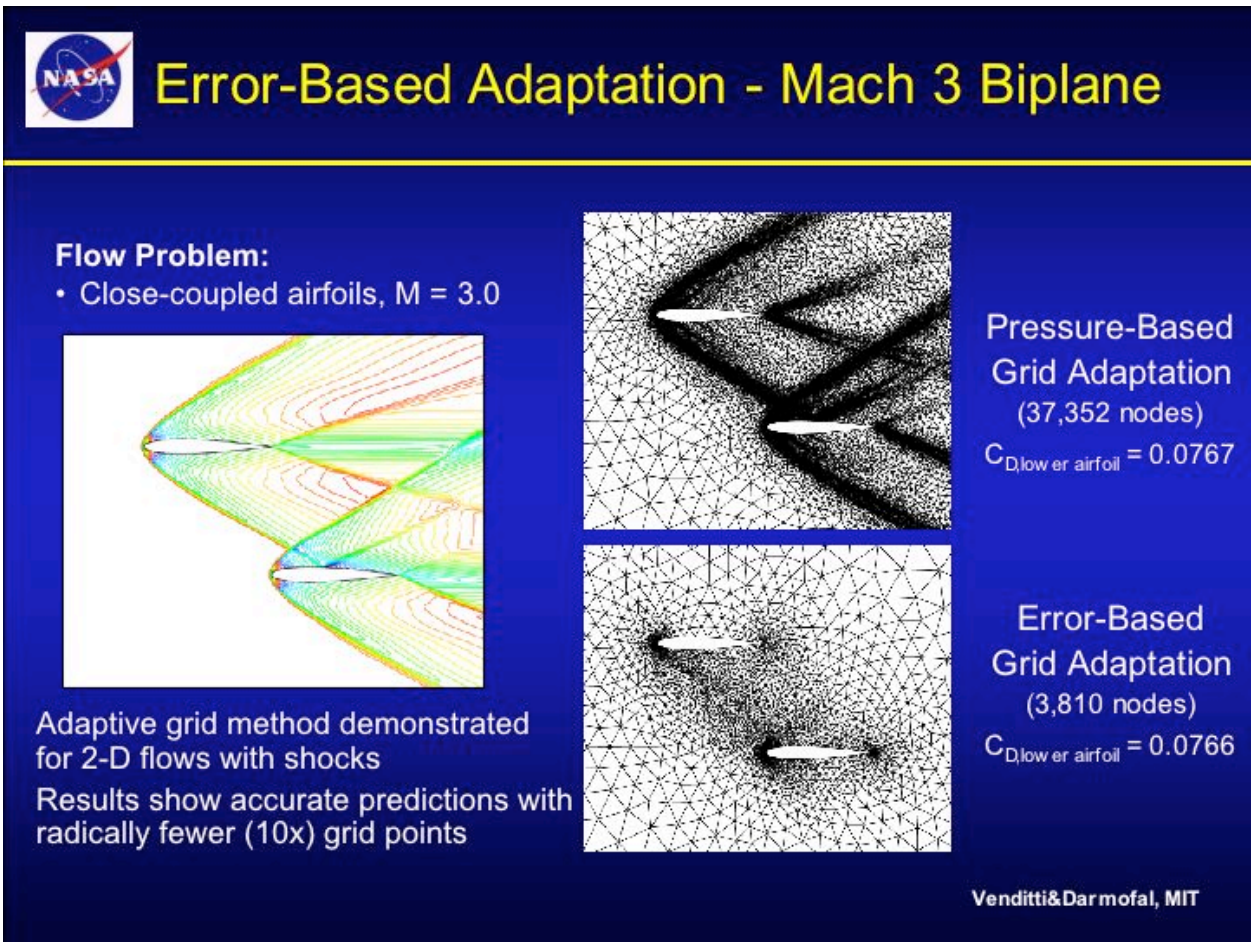


he may want to know the drag to within one count. (It should be noted that "within one count" refers to the best solution that can be obtained given the choice of numerical scheme, turbulence model, geometrical fidelity, etc. – not necessarily to within 1 count of the "true" answer.) Given a solution on a baseline grid, the method adapts the grid to minimize the primal and dual equation errors, and thus dictates where the mesh is refined. Furthermore, it provides a means to automatically terminate the process when the error is less than the specified tolerance.

This slides shows an application of error-based adaptation to supersonic inviscid flow past a staggered pair of airfoils – a Mach 3 biplane if you will.

On the left is the flow pattern that is obtained on a very-well resolved grid. The shock waves and their interactions are all captured quite well, with very sharp resolution of the shocks. On the top right is a solution adapted grid where the pressure gradient was the feature chosen as the adaptation criterion. The final grid contains nearly 38,000 points, and the computed drag coefficient on the lower airfoil drag is 767 counts.

On the lower right is the grid that results when the error-based grid adaptation method is used.

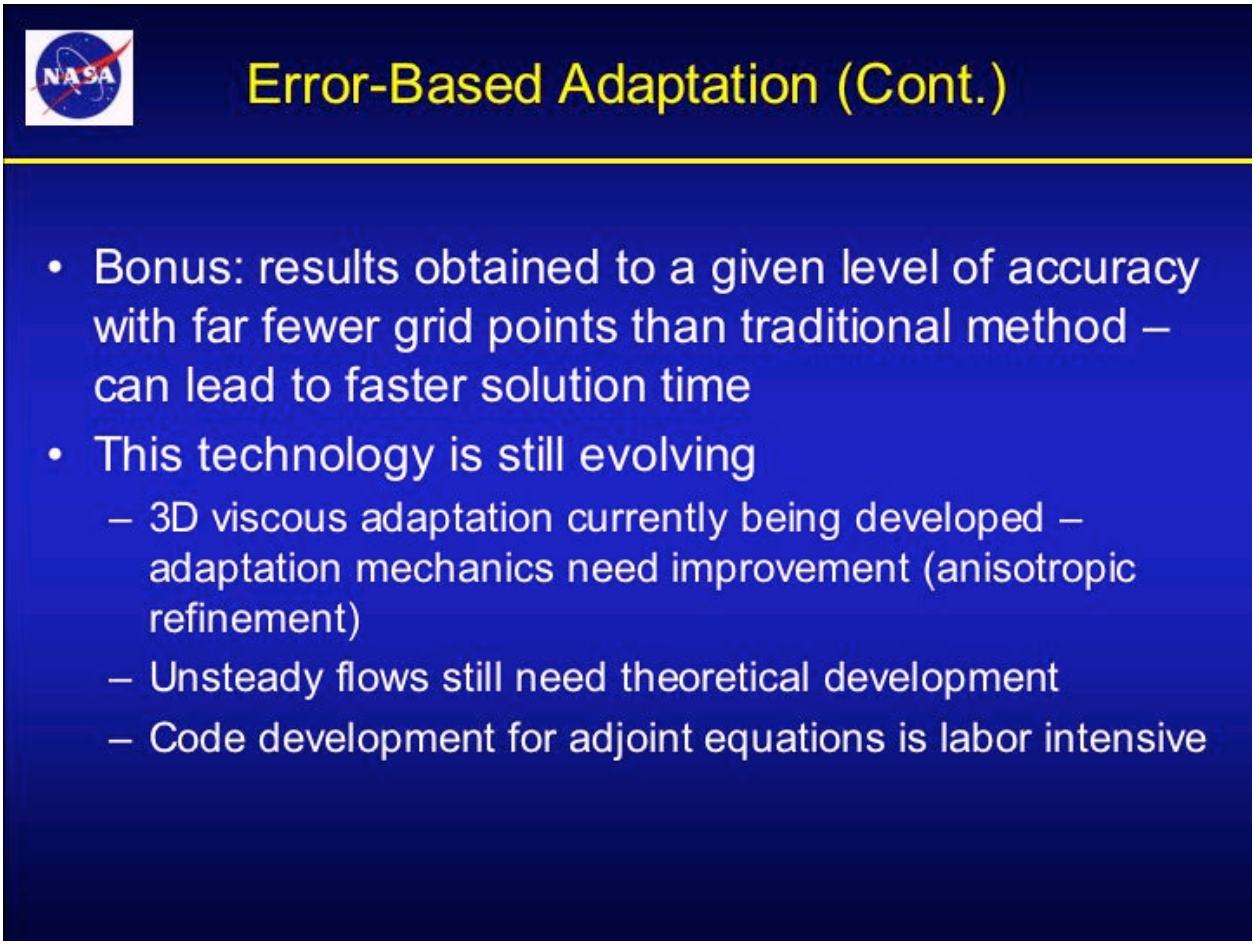


With only 3800 nodes – ten times fewer than the pressure based adaptation – the computed drag coefficient on the lower airfoil is 766 counts.

Notice that the error-based method has not resolved many of the flow interactions that one might think are absolutely necessary to resolve for an accurate prediction of the drag in this supersonic flow. In fact, apart from the leading and trailing edges, the only readily discernable feature that has been adapted to is the part of the bow shock from the upper airfoil that impinges on the lower airfoil.

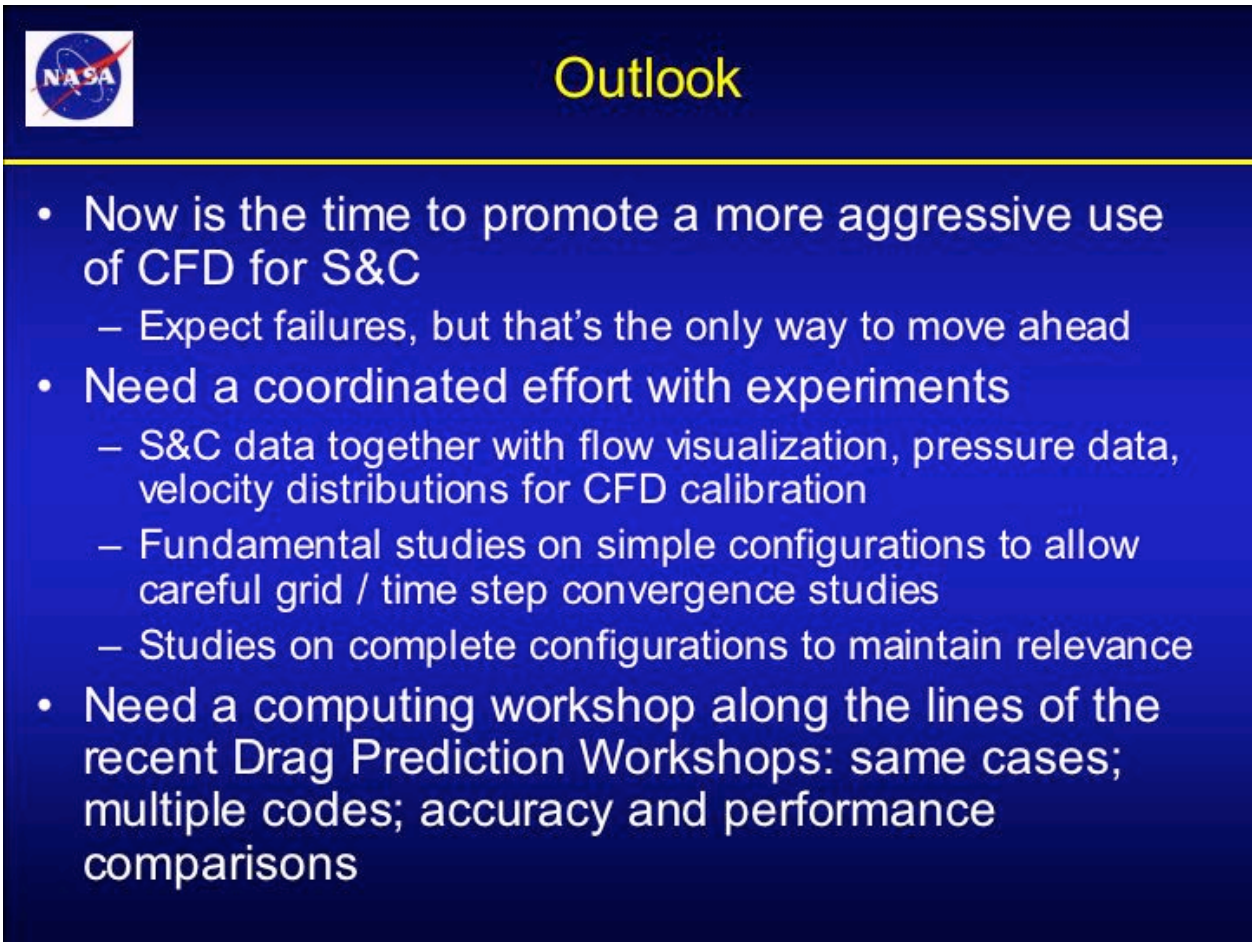
The relatively simple example on the previous slide suggests that in cases of complex flow interactions, intuitive, ad-hoc adaptation schemes may be quite wasteful of grid points, leading to needlessly long computation times.

The remarkable savings in grid points has been seen in many other cases, including viscous flows. However, we should be careful not to oversell this methodology at this point. It is still evolving, and some significant difficulties lie ahead. For viscous flows, much development work still needs to occur in the adaptation mechanics for highly anisotropic cells. Unsteady flows, which may be quite important in S&C applications, still need theoretical development. The method as developed to date relies on a convergent solution to a steady state. Finally, it should be noted that the development of the adjoint solver is very labor intensive.



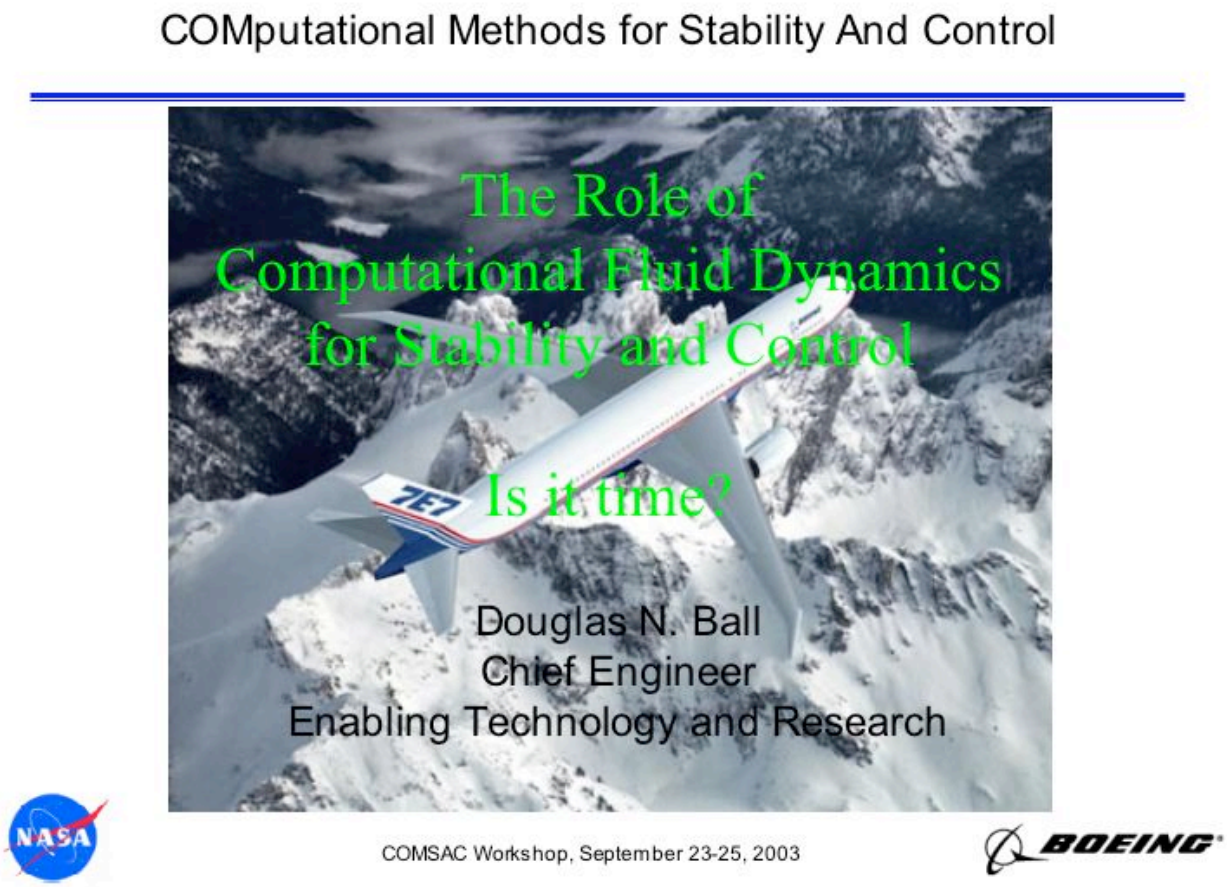
We believe that now is the time to promote a more aggressive use of CFD for S&C. There will be failures – they are to be expected – but that is the only way to make progress.

We feel that a coordinated effort between experiment and CFD is required. In addition to the usual force and moment data that the comes out of experiments geared toward S&C, more detailed information, including flow visualization, pressure data and velocity distributions are needed for CFD calibration. Such coordinated studies should include fundamental studies on simple configurations – to allow for careful grid and time step convergence studies – as well as studies on complete configurations of interest to industry in order to maintain relevance.



Finally, we believe that a computing workshop along the lines of the recent Drag Prediction Workshops should be held for a problem of interest to the S&C community. In these workshops, multiple codes are applied to the specified configuration (using supplied grids and/or grids of the participant's making), with comparisons made to experiment for assessing accuracy.

Over the past 25 years the field of Computational Fluid Dynamics has made tremendous strides. Wings can be designed and tested with complete confidence that the results will be as expected. Their reliability and range of applicability has grown. Now is the time to explore what can be done with CFD at the corners of the flight envelope.



My presentation is broken down into three areas:

1. A description of the kinds of "surprises" that Boeing Commercial Airplanes has experienced in the last 25 years;
2. A sampling of the kinds of CFD modeling that we are doing in support of stability & control and loads issues
3. A brief discussion as to how we, as an government/industry/academia team might operate.

Outline

Flight test experiences in the 80's and 90's

Current CFD work related to stability and control issues

The COMSAC program – possible "rules of engagement"

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The 777 had many miss-predictions that were discovered during flight testing. None of them major, but things that had we known about them during the design phase we would have designed a different airplane. An example of this is the fact that the airplane is nearly .01Mach faster than planned. Had we known this we could have reduced the sweep of the wing to improve low speed performance and reduce weight or thickened the wing to reduce weight and increase fuel volume.

The 737NG family had several “surprises of its own”.

737-600/700/800/900 (NG)

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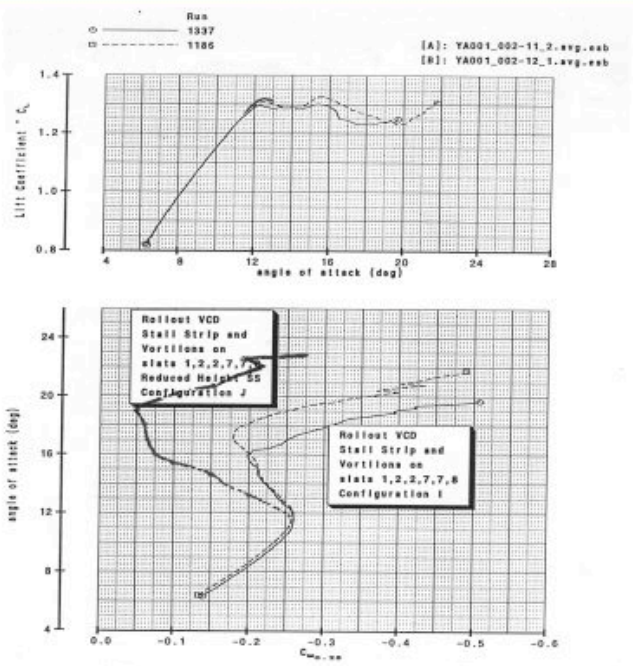
The flaps-up stall characteristics turned out to be unacceptable. The airplane exhibited too much stick lightening during stall (pitch up. The dark black line on the left of the plot show the pitch characteristics for the rollout configuration.
The addition of a stall strip on the inboard wing leading edge and three vortilons on the outboard slat improved the stall characteristics.

737NG Flaps Up Pitch-Up



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These drawings show the size and location of the inboard stall strip

737NG Flaps Up Pitch-Up

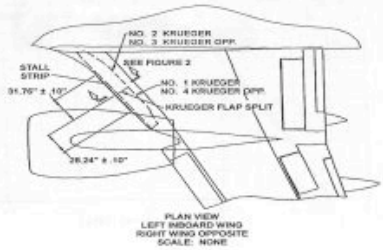

Figure 11 Stall Strip Span Location

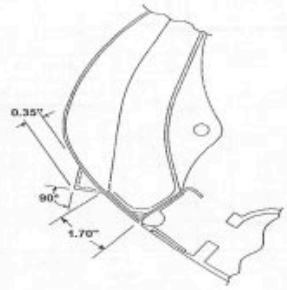

Figure 12 Stall Strip Dimensions and Height Location

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These drawings show the size and location of the vortilons on the outboard slats.

737NG Flaps Up Pitch-Up

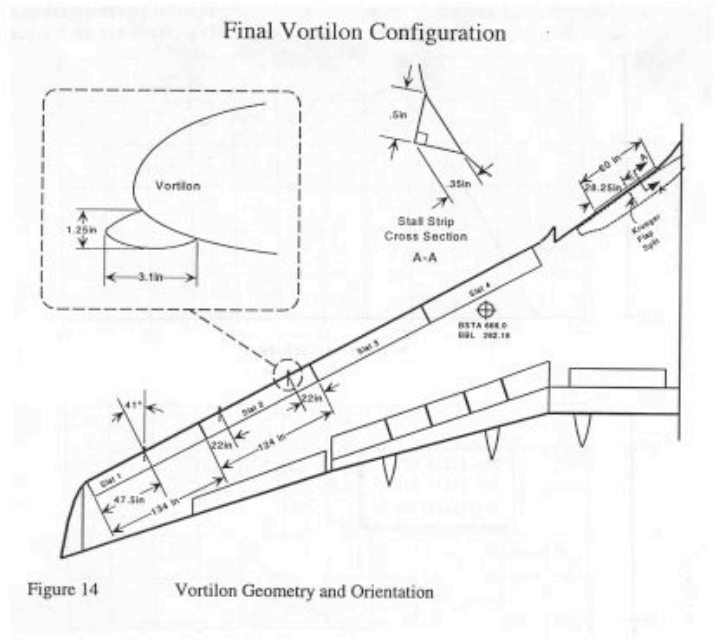

Figure 14 Vortilon Geometry and Orientation

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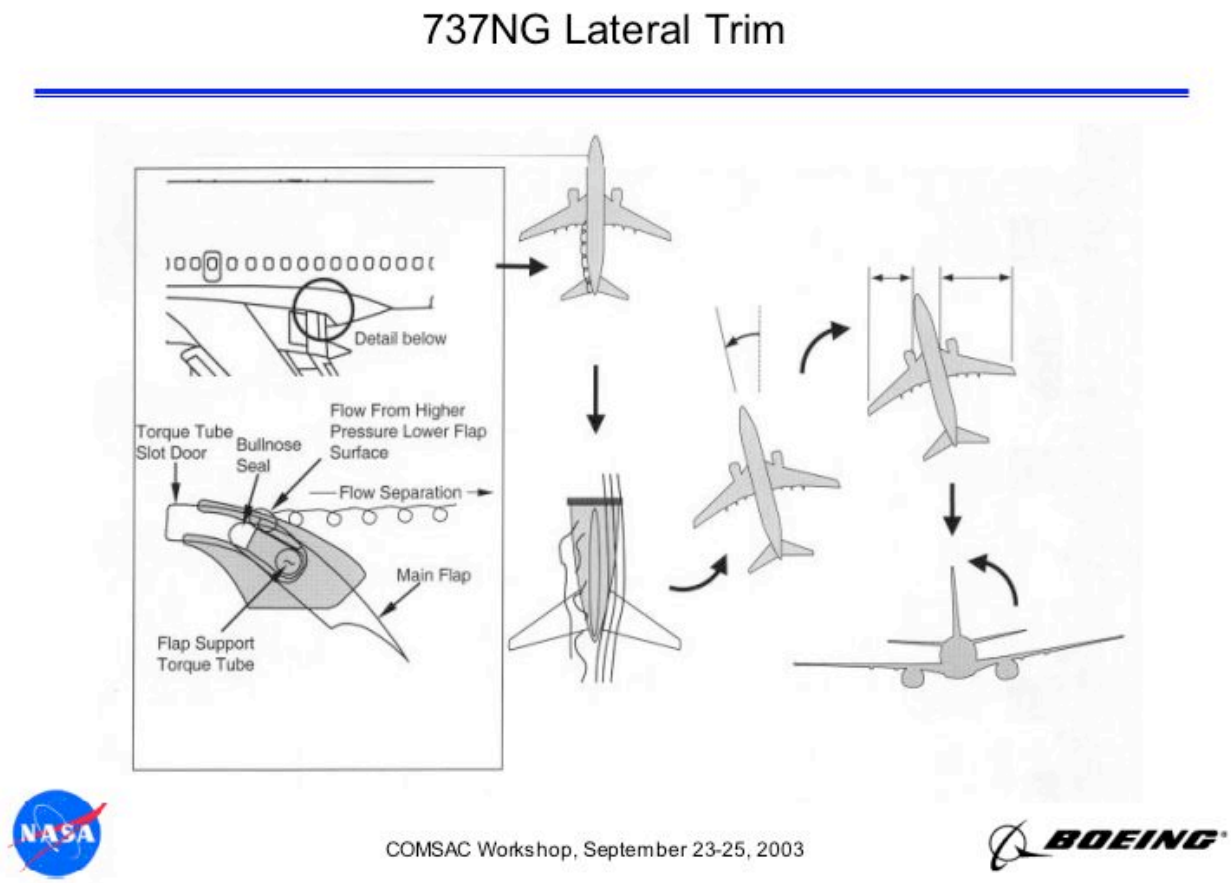
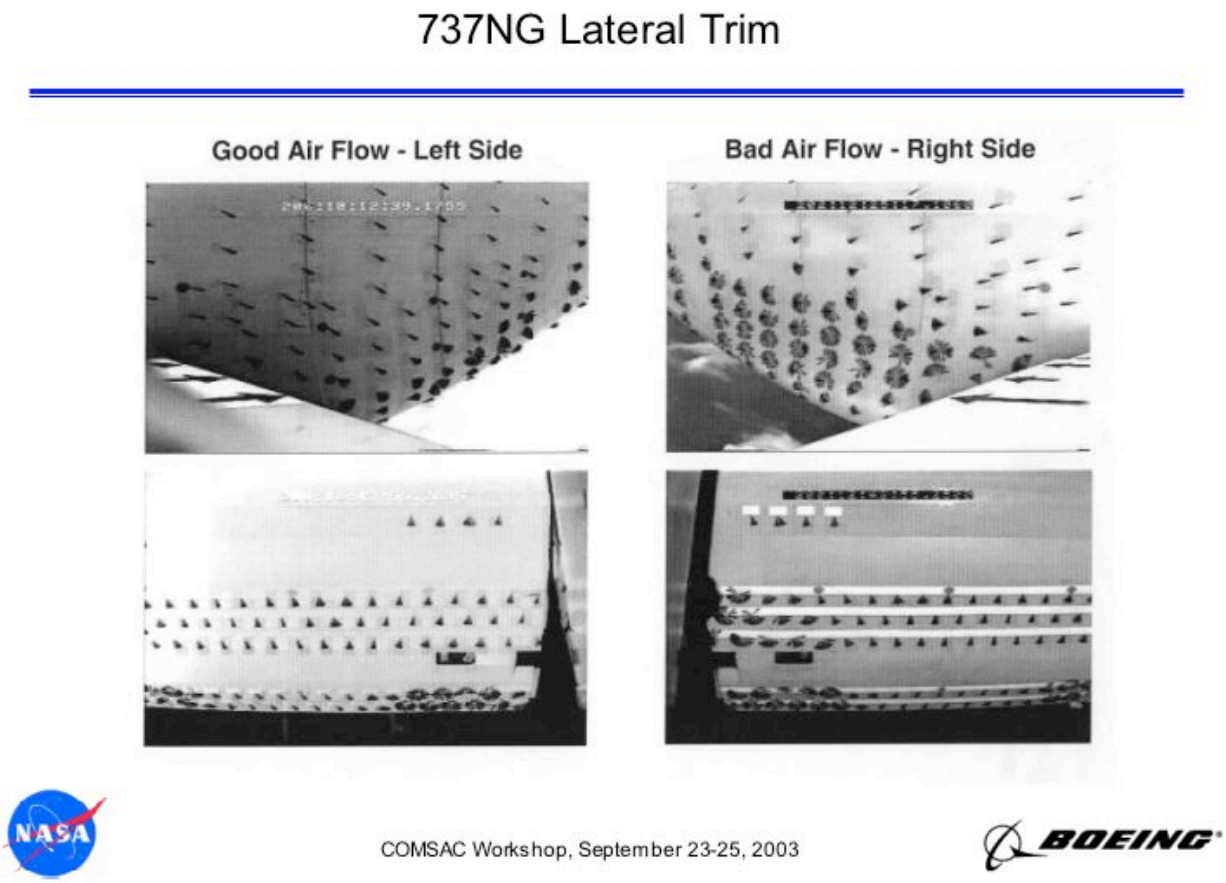
Another issue for the 737NG was a lateral trim issue. The story goes like this:
If the trailing edge flaps aren't rigged quite right they can separate. The figure shows the left hand flaps separating. This separation flows back and blankets
one side of the vertical tail. The velocity difference across the tail causes the tail to yaw the airplane nose left. As the airplane yaws the left wing increases in sweep and the right wing decreases in sweep. This causes a decrease/increase in their lift curve slopes thus creating more lift on the right wing and less on the left. This lift imbalance causes the airplane to roll left wing down.

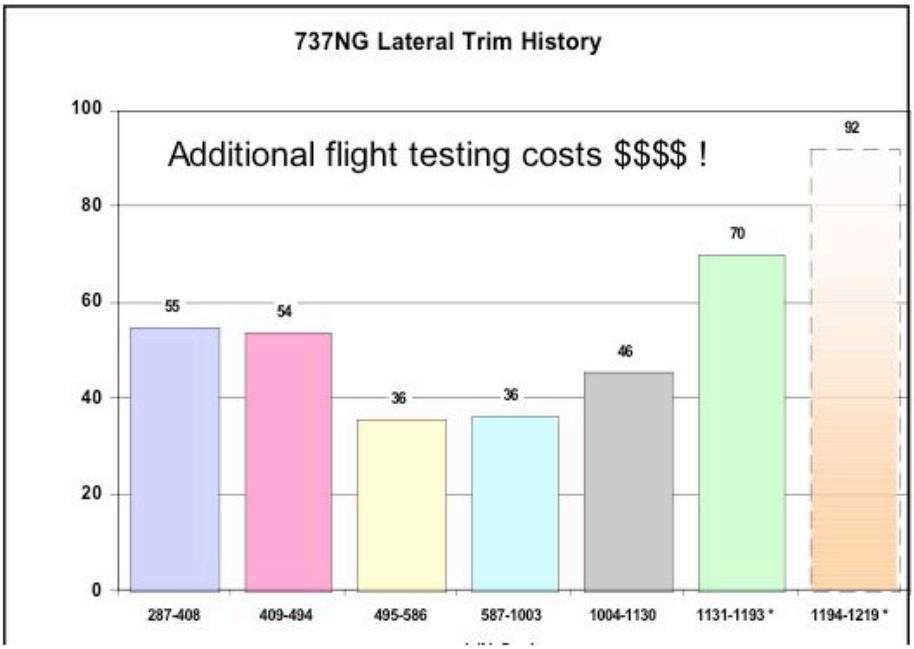


Here are flight test photos showing normal flow on the flap and side of body in the pictures on the left, and separated flow on the right.



This problem has caused us to have to rerig and refly predelivery flight tests until the problem has been resolved. This can cause delay in delivery (and revenue) as well as the additional costs of the extra flight tests

737NG Lateral Trim



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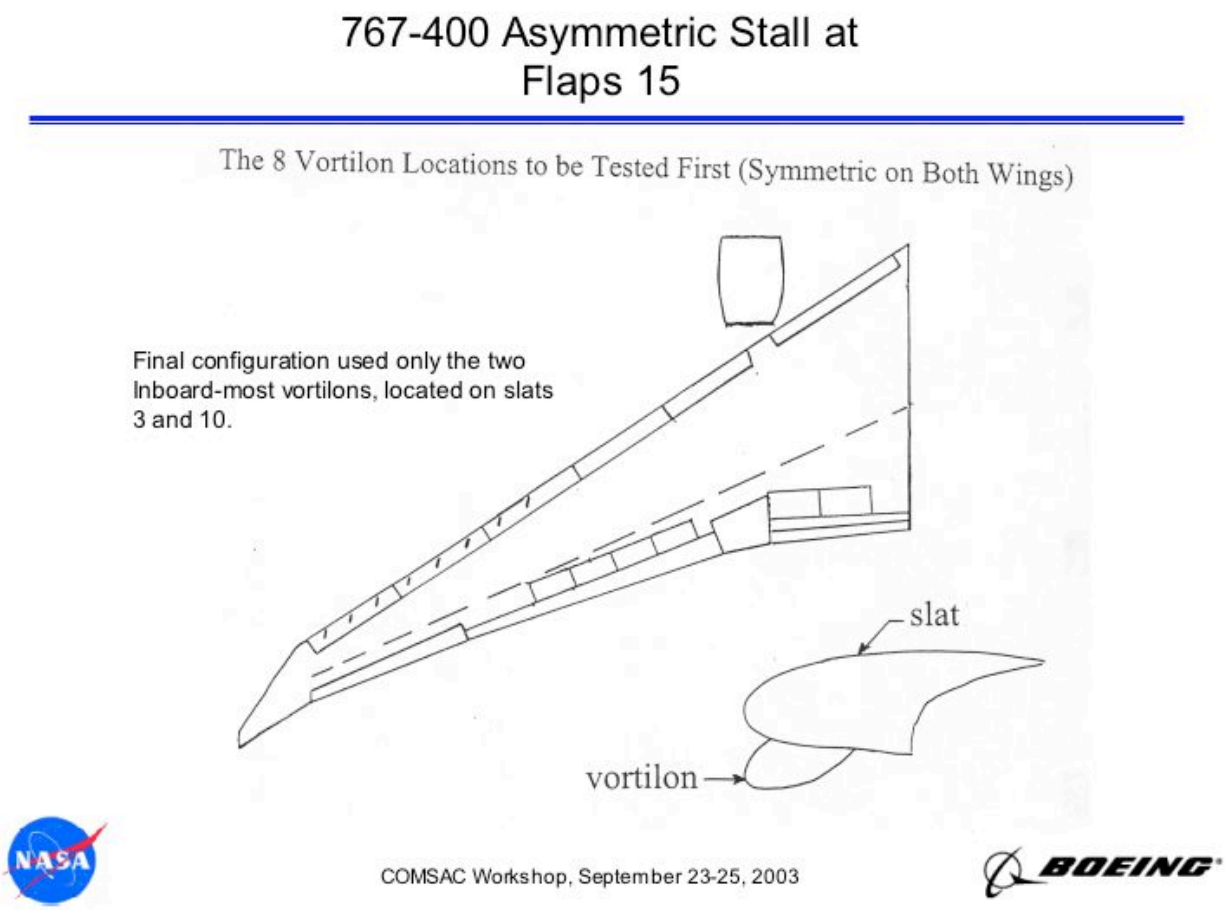
An asymmetric stall on the 767-400 at flaps 15 was resolved with the use of vortilons across several of the outboard slat segments



So what are the emerging capabilities in CFD that may help us to avoid these kinds of surprises on future airplanes?

Emerging Capabilities

2003

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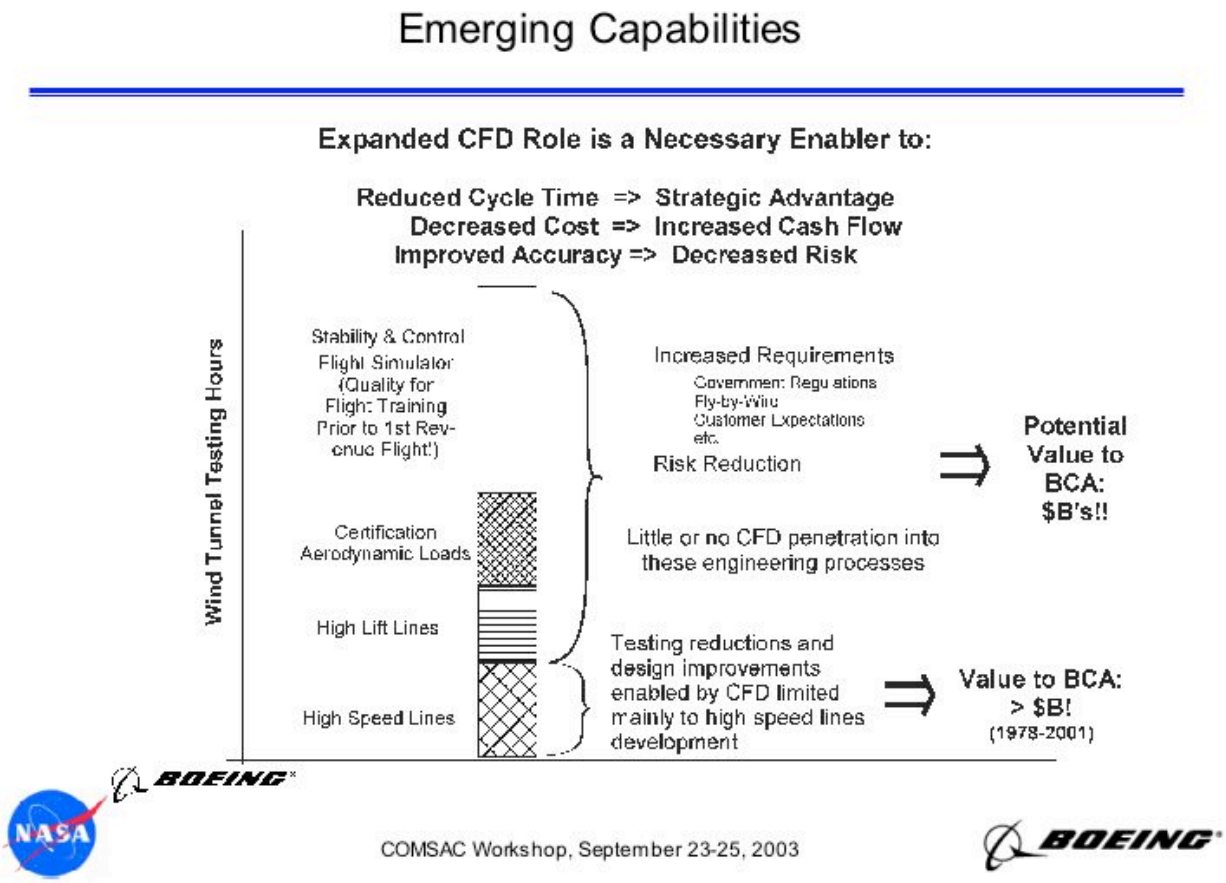
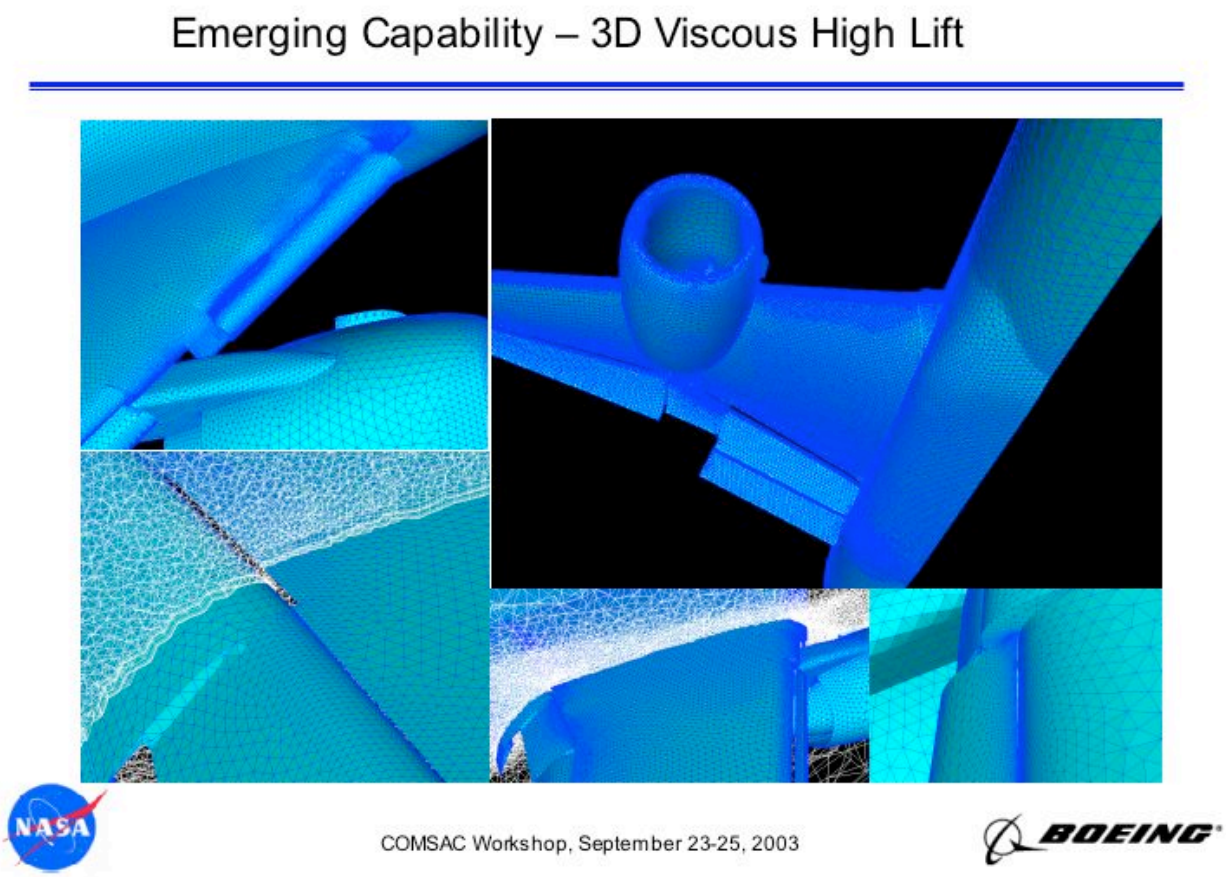
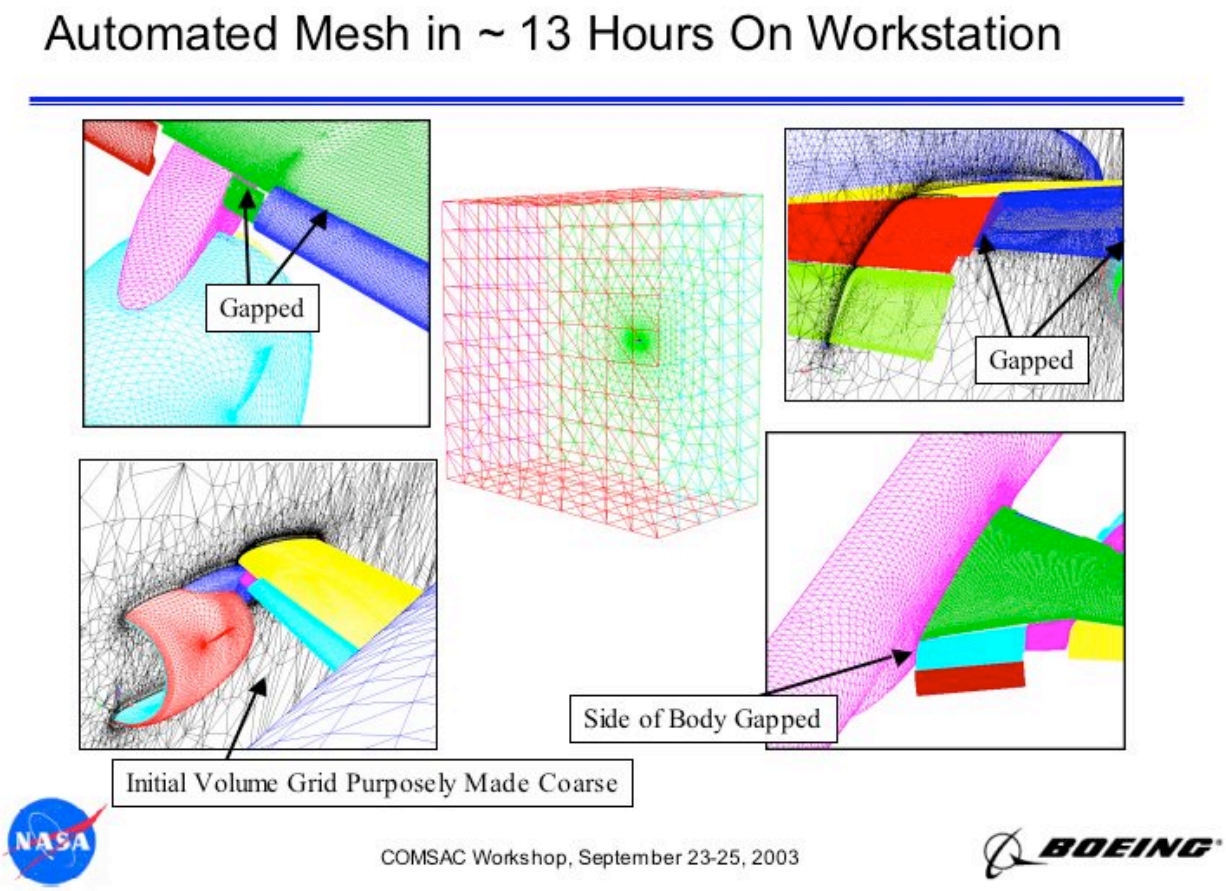
There is no question as to the economic impact the successful application of CFD throughout the flight envelope will have. We have gone from building and testing 77 wings on the 767 to 11 for the 737NG. This is a huge savings in both
money and time. The areas of high lift design, stability and control validation and simulator database development, and loads database development will all reap huge rewards from the intelligent application of CFD.



Unstructured grid technology makes it now possible to model configurations having a great degree of geometric complexity.

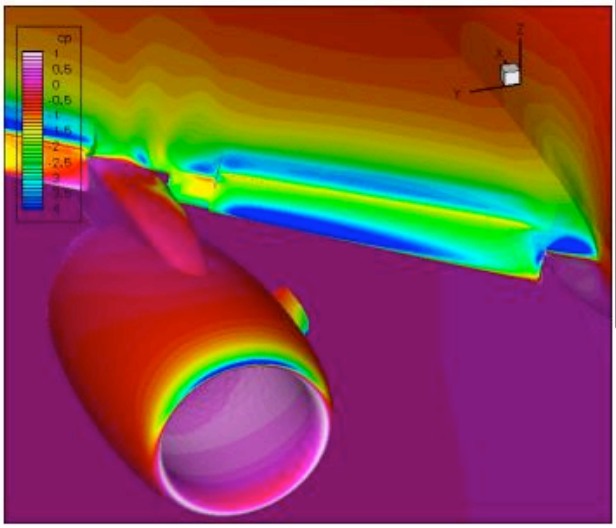


Examples showing the nature of the unstructured grid used to model the 777.



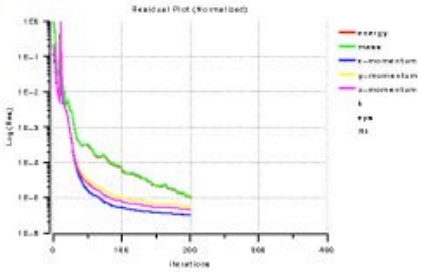
Using automated gridding procedures it is now possible to get converged solutions for high lift configurations in a matter of a few days – instead of weeks or months. This solution was obtained using AFLR3 and CFD++

Elapsed Time for 1st Automated Solution 2 Days



Highlights:

- The automation worked!
- Scripts are robust enough for automated grid resolutions studies.
- Obtained converged solutions first try, wall clock time ~8 hours, 68 CPUs.
- Initial (coarse) grid size 15 million cells.
- Accuracy improved over manually created mesh despite more model differences and coarser mesh.



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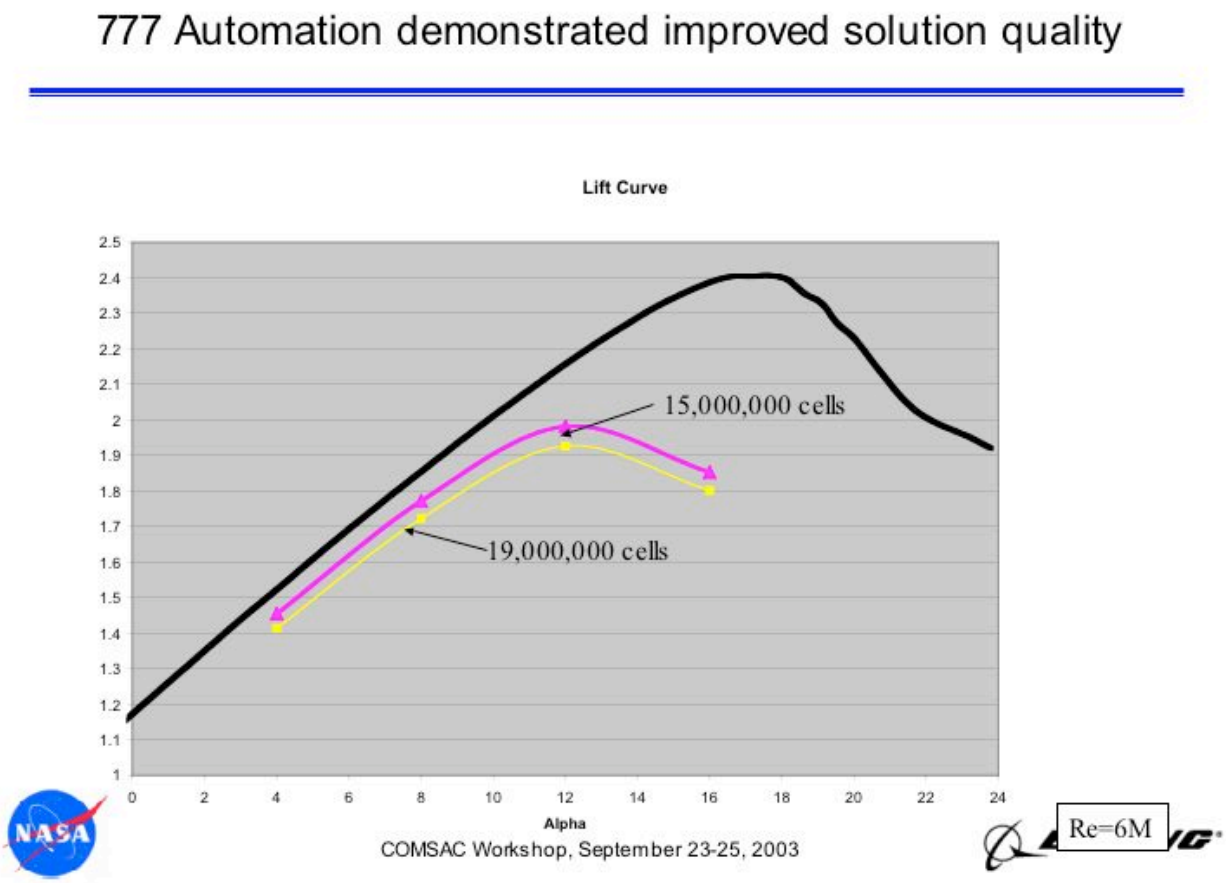
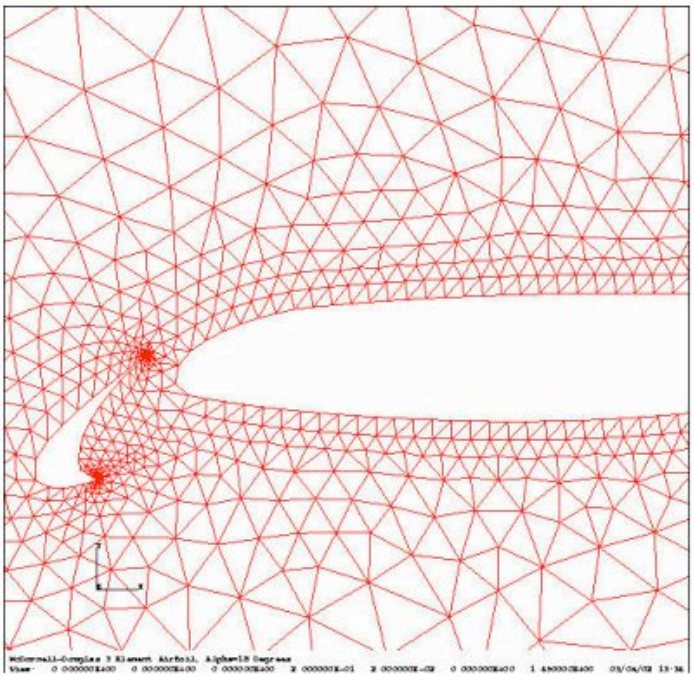
No, it's not perfect yet, by a long shot. But if we are to do any investigations of low speed stability and control issues we must first be able to compute the basic wing/body characteristics.



Solution adaptive techniques, like the one shown here, will help to mitigate the ever-increasing need for larger and larger computers. This will allow grid to be placed only where it is needed and minimize it everywhere else.

Emerging Capability – Solution Adaptation

- Grid Generation
  - Need To Know Solution In Advance
- Full Envelope Simulations:
  - Don't Know Where Separation Will Occur
  - Unstructured Grid
  - For General Geometry



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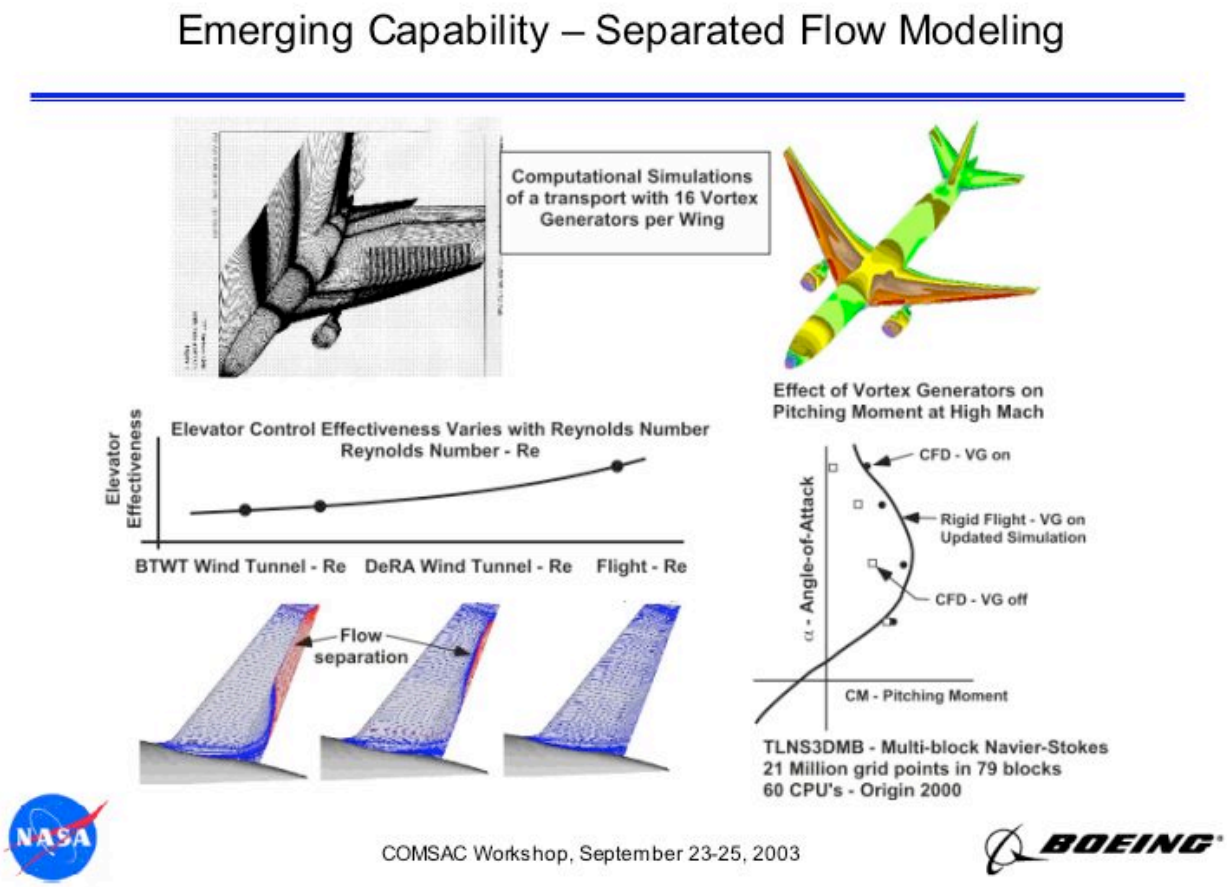
Two modeling efforts are shown here. In the bottom left we have used CFD to model the effect of changing Reynolds number. The elevator on the left, operating at atmospheric wind tunnel conditions, is separated. As the Reynolds number is increased toward flight the separation is seen to disappear, thus increasing the effectiveness of the elevator.

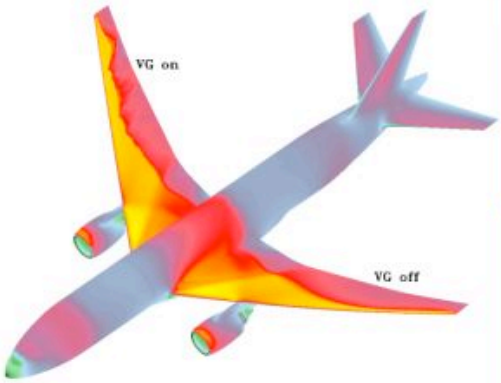
The other three figures (top left, top right, bottom right) show the effect of modeling the wing-mounted vortex generators. Roughly 23 million grid points were used in the block structured code to model the 777 with 16 VG's

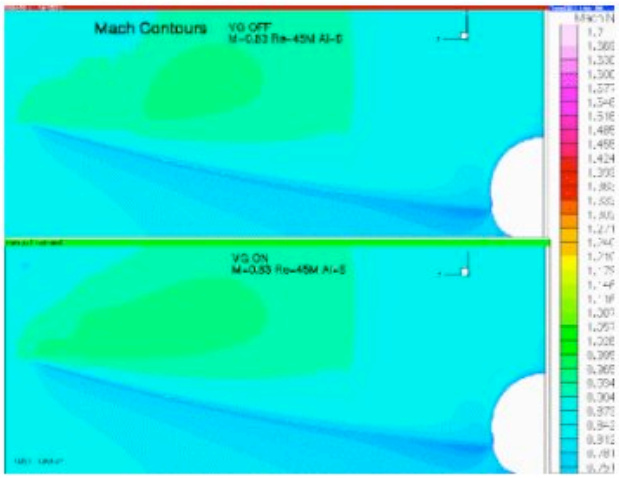


Here are two videos comparing the wing with and without vortex generators. Notice how much longer the wing stays attached when the VGs are present.

Emerging Capability – Separated Flow Modeling

- **Provide critical pre-test airplane stability and loads data, thus reducing wind tunnel testing and design cycle time**
- **Provide Reynolds number corrections for wind tunnel data to avoid costly fixes during flight test.**
- **Enables common aerodynamics database between S&C and Loads**
- **Develop Loads and S&C processes using CFD aerodynamic data**





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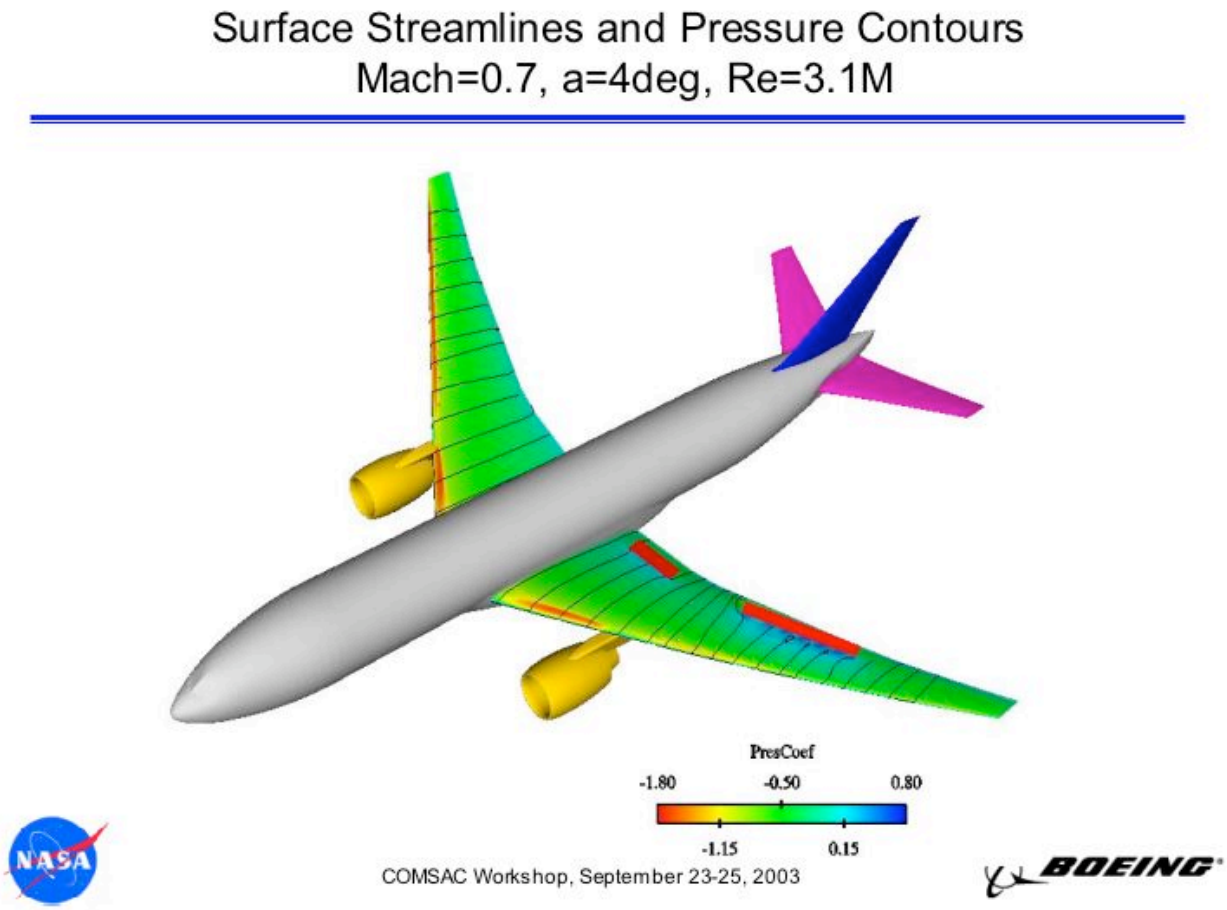
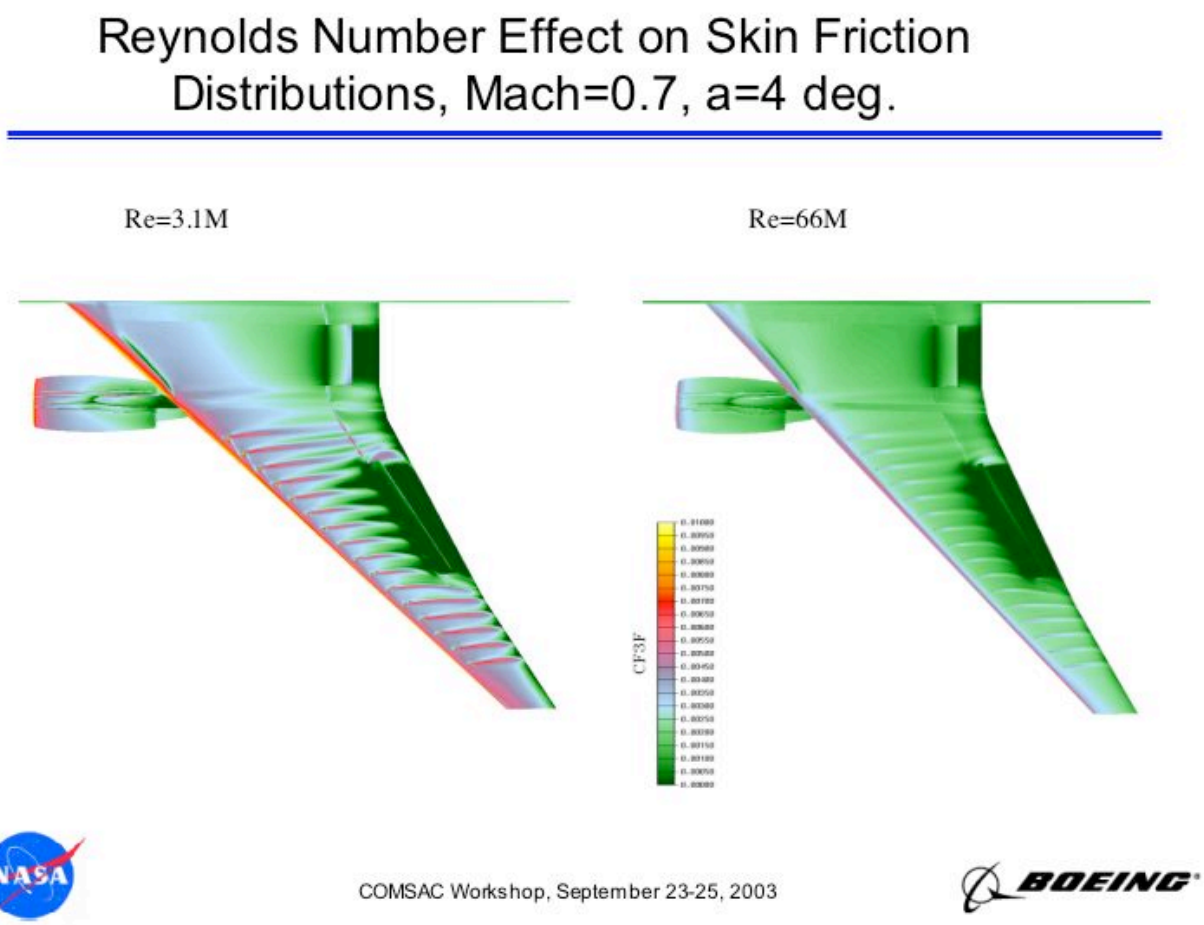
We have discovered that in order to more accurately predict the effectiveness of spoilers we must model the wing mounted VGs ahead of them. Here the right wing has the spoilers down, the let wing has them deployed.

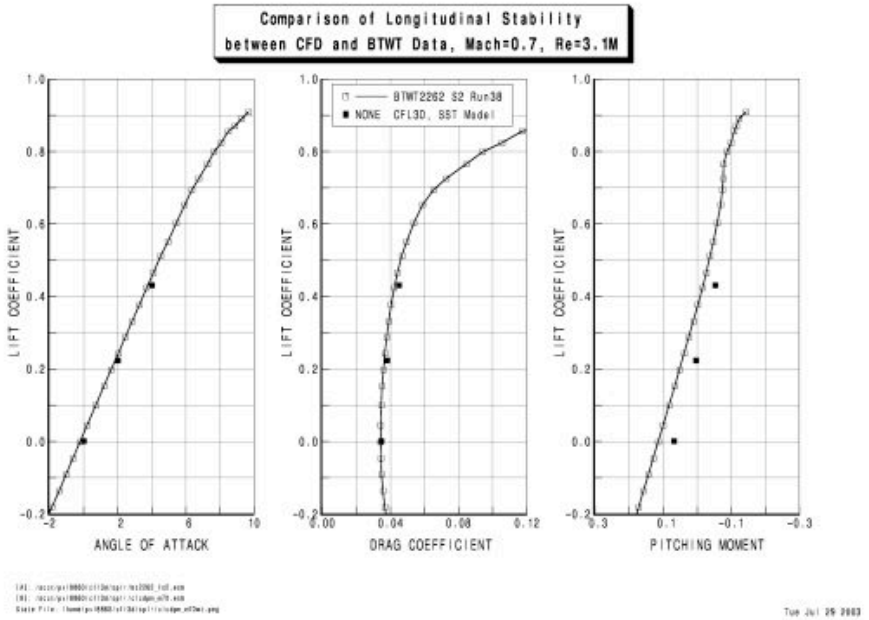


Here you can see the affect of Reynolds number on the flow field ahead of the spoilers.



Here you can see the lift curve, drag polar, and pitch characteristics. Clearly the CFD has done a good job of modeling the airplane.

Forces and Moments – 777 – Spoilers Deflected



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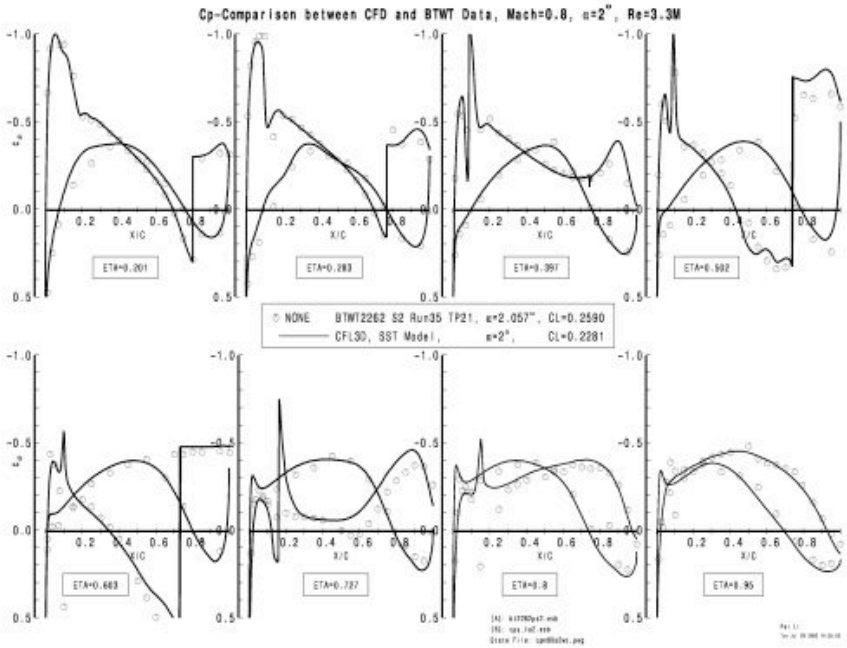
A comparison of wing pressures with CFD calculations shows stunning results.

Section Cp's – 777 – Spoilers Deflected



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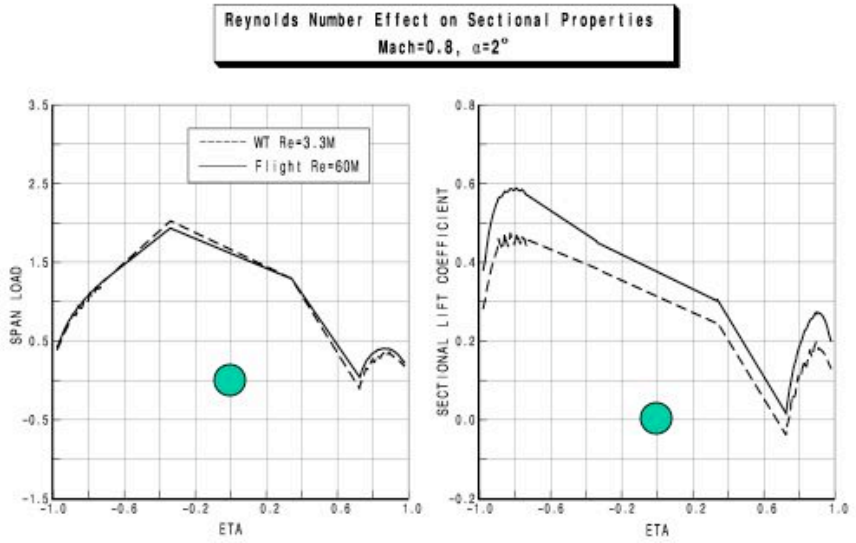
Here you can see the section Cls and span load. The circle represents the airplane fuselage – imagine it coming out of the page. The right wing is carrying its normal load – the spoilers are deployed on the right hand wing. The left wing shows the dramatic lift loss due to the spoilers.

Full Airplane Span Load Effects



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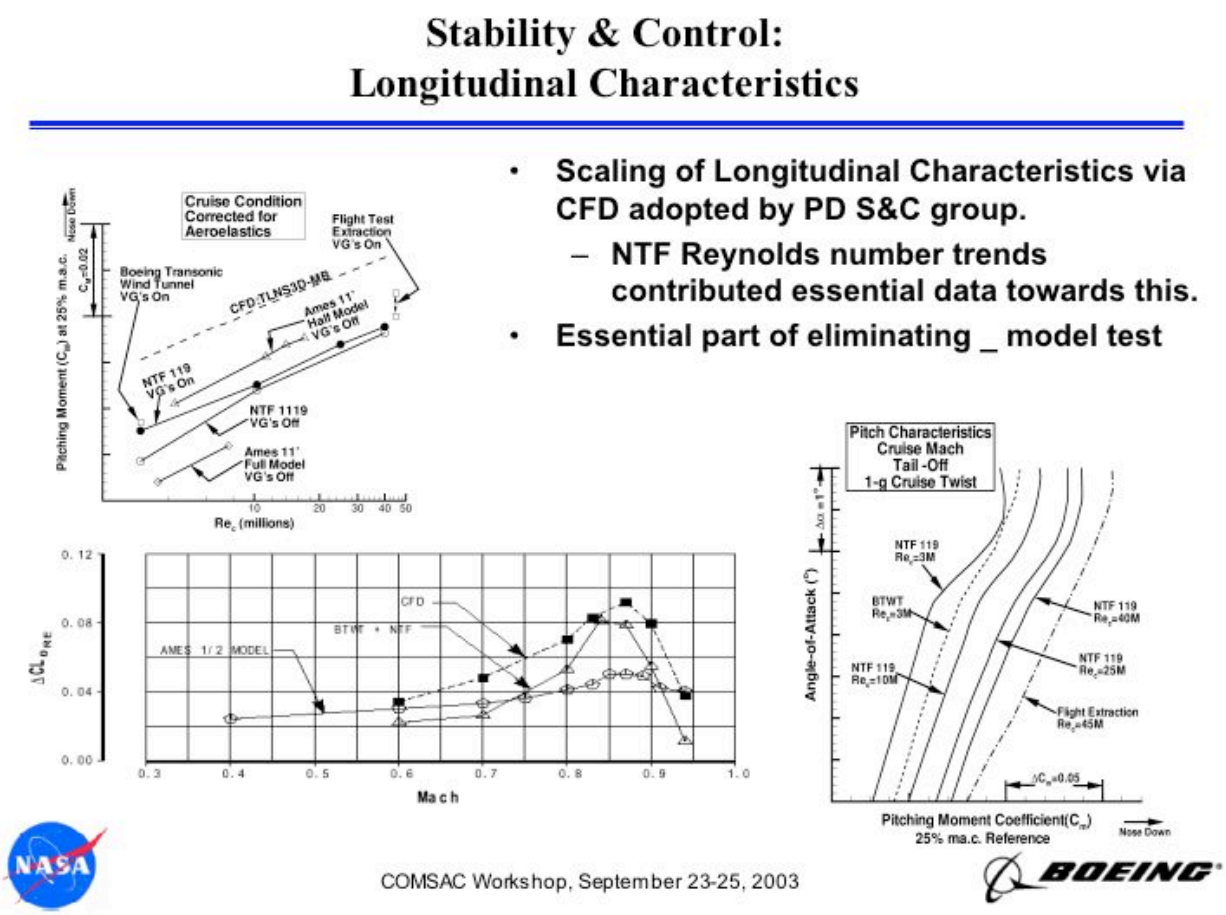
Here you can see the effect of increasing Reynolds number of the aft loading, pitch characteristics, and lift at zero angle of attack.



So how do we go about doing all this work? Well, to be in COMSAC you should have to bring something to the table. In my view that means airplane configurations, wind tunnel data, flight test data and the people to do the analysis work. This is the "cost of admission" – oh yeah, you have to be willing to share it with the other team members.

I don't think we need a great many people – just the right ones. And they need access to best computing resources that we can make available. If NASA could provide the computing then industry could provide the people.

Suggested program environment

- The price of admission is data – and data sharing
- The number of people engaged is kept small – and paid for by their own organization (80/20). These people have free and open access to timely computing resources.
- Inside the program we can all see what is being done by everyone – at least the undisguised results
- Outside world sees practically nothing
- Can NASA create this "black program" environment?

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Security is a huge issue. Can we create an environment like a classified program where the participants see everything and the outside world sees nothing? It will make it easier to open up if we're protected from interested, "prying" eyes.

NASA – can you make this happen?

I have secured the permission of Boeing management to allow the release of 777 geometry, wind tunnel, flight test and CFD results within the COMSAC arena – provided the proper security measures are in place. We need protection from Airbus, Embraer, and others.

We are prepared . . .

- To release, within the COMSAC umbrella, 777 geometry, wind tunnel and flight test data along with any analyses that are generated within the COMSAC arena . . . provided this information is kept within COMSAC and the partnering organizations and cannot be accessed by people outside the program.

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Thank you for your time. I am looking forward to working with each of you as we work to make the COMSAC idea a reality. I believe there is much to be gained for engaging in this activity and will work diligently to make it happen. I hope you will, too.

Thank you for listening . . .

COMSAC Workshop, September 23-25, 2003


AIR COMBAT SYSTEMS
Northrop Grumman Perspectives on COMSAC
23 September 2003
NASA Symposium on Computational Methods for Stability And Control (COMSAC)
23-25 September 2003 Hampton, Virginia
NORTHROP GRUMMAN

Northrop Grumman Perspectives/Experiences

Outline

- Impact of Inaccurate Aerodynamic S&C Predictions
- Potential Benefits of Complementary Use of CFD and Wind Tunnels
- Northrop Grumman Experiences/Perspectives
  - Lessons Learned
  - Flight Testing
- Summary and Recommendations

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Impact of Inaccurate S&C Predictions

- *Types of Aircraft Modifications After First Flight*
  - *Change to Larger Horizontal Tail Size for Longitudinal Stability and Control*
  - *Add Ballast for Longitudinal Stability*
  - *Change to Larger Vertical Tail Size for Directional Stability*
  - *Add Wing Fence for Lateral Stability*
  - *Wing Camber Changes for Stall or Pitch Trim*
  - *Resize Actuators Due to Larger Than Expected Control Surface Hinge Moments*
- *Operational Limitations*
  - *Impose AOA Limit to Prevent Deep Stall Hang Up*
  - *CG Restrictions on Payload and Fuel to Maintain Stability*

Impact of Inaccurate S&C Predictions

- *NGC Experiences*
  - *F-5F Yaw Departures and Post Stall Lateral and Directional Instability Required Wing Fence, New LEX and New Radome Shape*

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Impact of Inaccurate S&C Predictions

- *Control Laws and/or Control Gain Changes*
  - *Modify Flap Schedule, Control Gains, or Control Laws*
  - *Implement a Modification to the Air Vehicle Computer Software Load*
    - *Software Regression Testing*
    - *EMI Retesting*
    - *Crew Rehearsals in the Simulator*
    - *Slip in the Flight Test Schedule*
  - *Cost in the $100K's*

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Program Impact of Inaccurate S&C Predictions

- *Loss of Flight Test Aircraft*
- *Additional Wind Tunnel Testing*
- *Investigate Multiple Solutions*
- *Fabrication of Mods for Flight Test*
- *Additional Flight Testing*
- *Impose Operational Limits if Mods Not Sufficient*
- *Schedule Delays*
- *Increased Program Risk, Cost, and Scrutiny*

Northrop Grumman Perspectives/Experiences

- *Potential Benefits of Complementary Use of CFD and Wind Tunnels*
  - *Better Understanding of Flow Physics*
  - *Reduced Wind Tunnel Testing*
  - *Risk Reduction Prior to Flight Test*
  - *Reduced Design Cycle Time*

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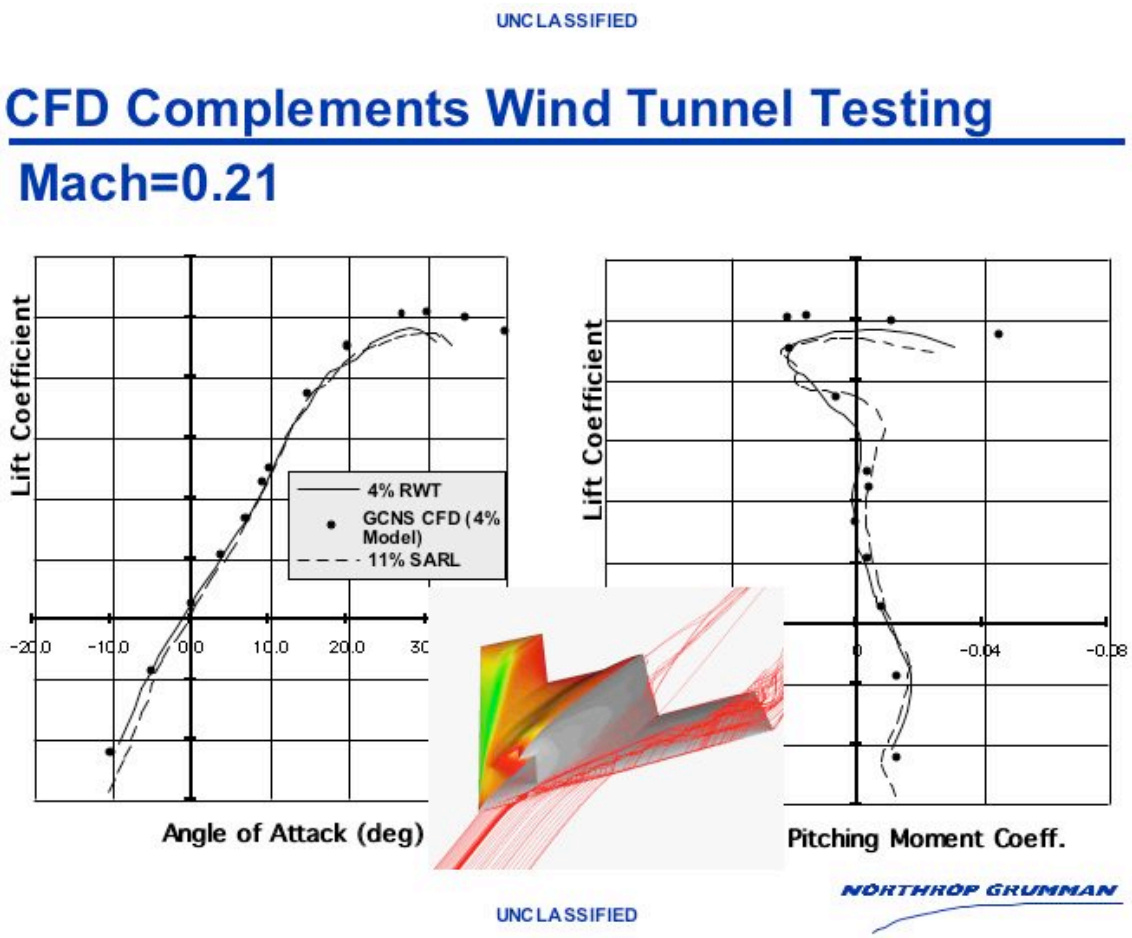
Excellent agreement up to 20 degrees. Pitch-up predicted. Max lift over estimated by 5 %.



Discrepancy between CFD and wind tunnel test increases with angle of attack. CFD provides flow physics insight to help size and locate control surfaces.

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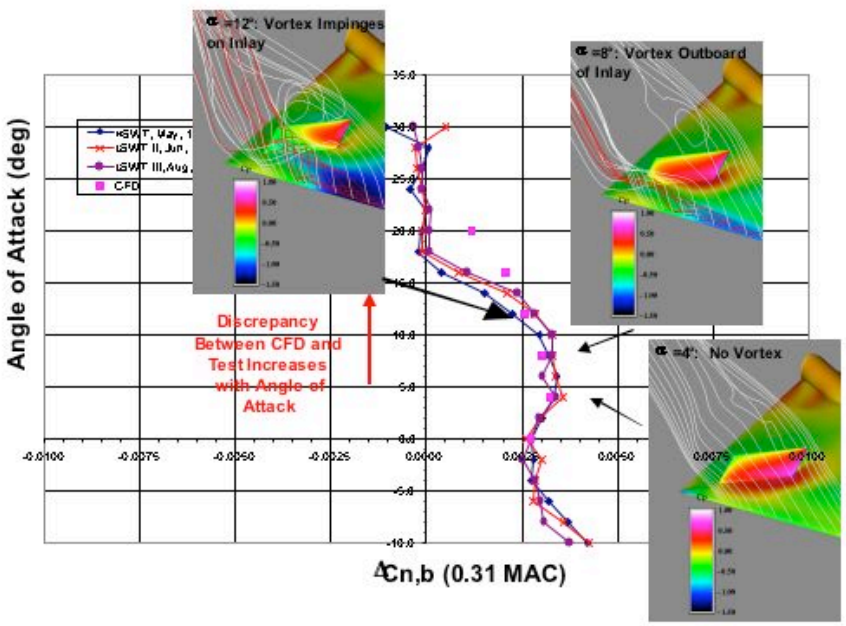
CFD Insight Into Flow Physics

Spoiler -30°, Mach=0.21



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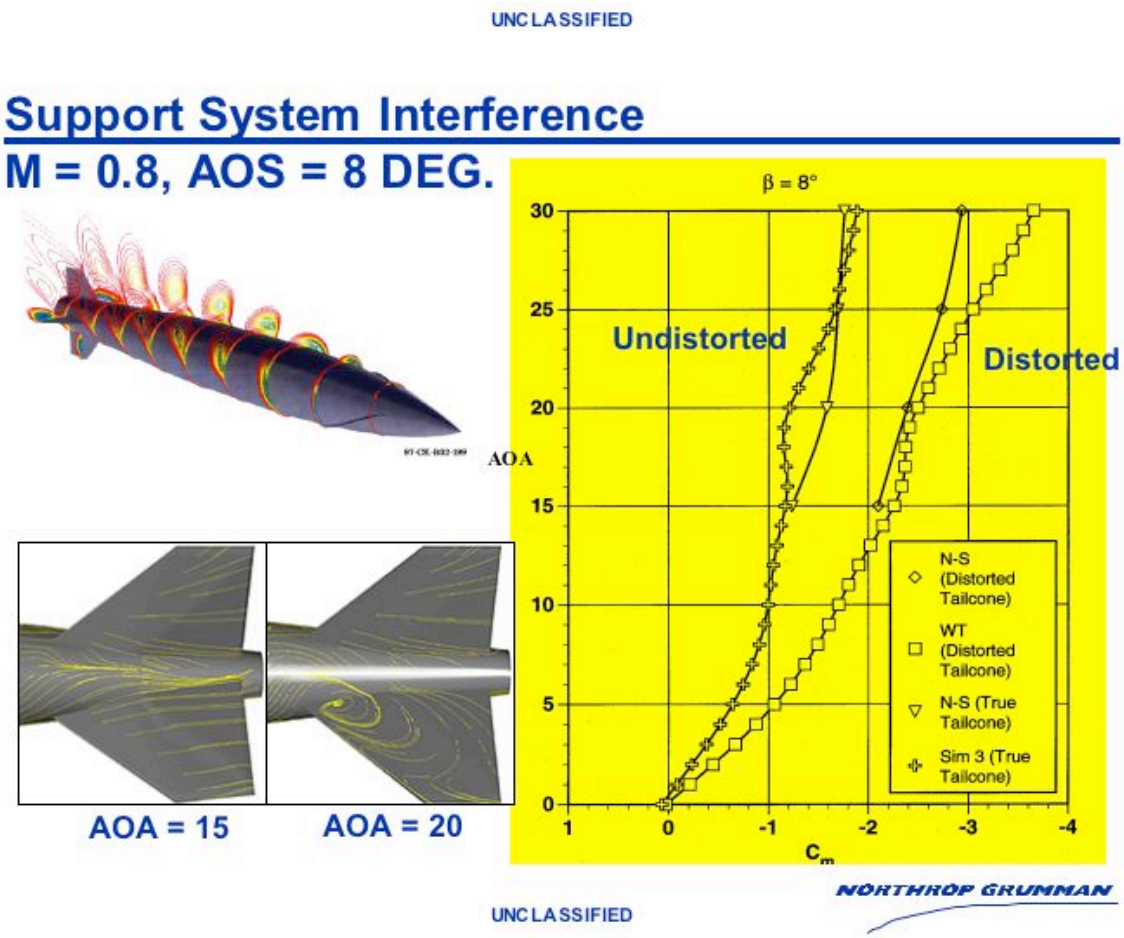
The loss in pitch stability due to removal of a distorted tail cone was under predicted using CFD. CFD provides flow physics insight for individual tail fins.



Northrop Grumman Perspectives/Experiences

Lessons Learned

- *Expect Aerodynamic Nonlinearities From Flow Separation Due to Shock Waves, Vortex Breakdown, and Wake Flow*
- *Aerodynamic Hysteresis Effects Can Occur in Sideslip Data as Well as in Pitch Data*
- *Asymmetric Forebody Vortex Shedding Responsible for Rolling and Yawing Moments at Zero Sideslip*
- *Testing in the Stall Angle-of-Attack Region Must be Done Using Small Increments in Angle of Attack or Sideslip (one degree or less) or the True Stall Characteristics May Not be Identified*

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Testing in the stall angle-of attack region must be done using small increments in angle of attack or sideslip (one degree or less) or the true stall characteristics may not be identified

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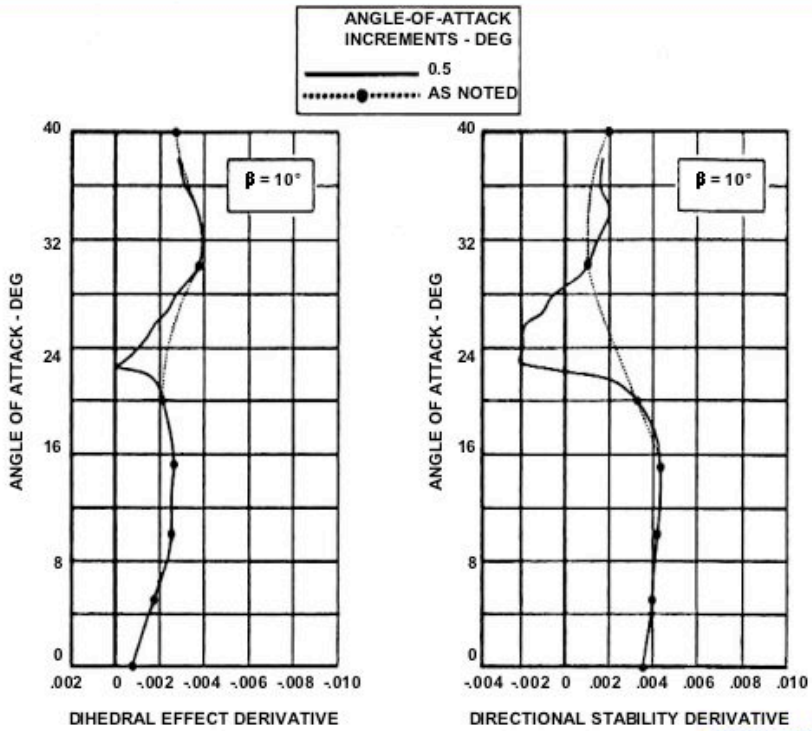
Effect of Angle of Attack Increments



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In the stall region and beyond expect aerodynamic nonlinearities from flow separation due to shock waves, vortex breakdown, and wake flow.

Aerodynamic hysteresis effects can occur in sideslip data as well as in pitch data. Are there limitations in current CFD to predict hysteresis?

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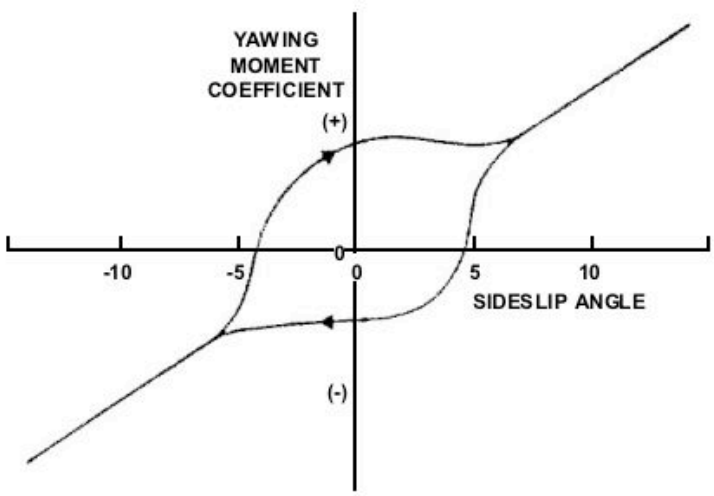
Aerodynamic Hysteresis in the Stall Region



Can Current CFD Predict Adequately?

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Wind tunnel accurately predicted non-zero yawing moment caused by asymmetric vortices, but what success rate do we have with CFD?

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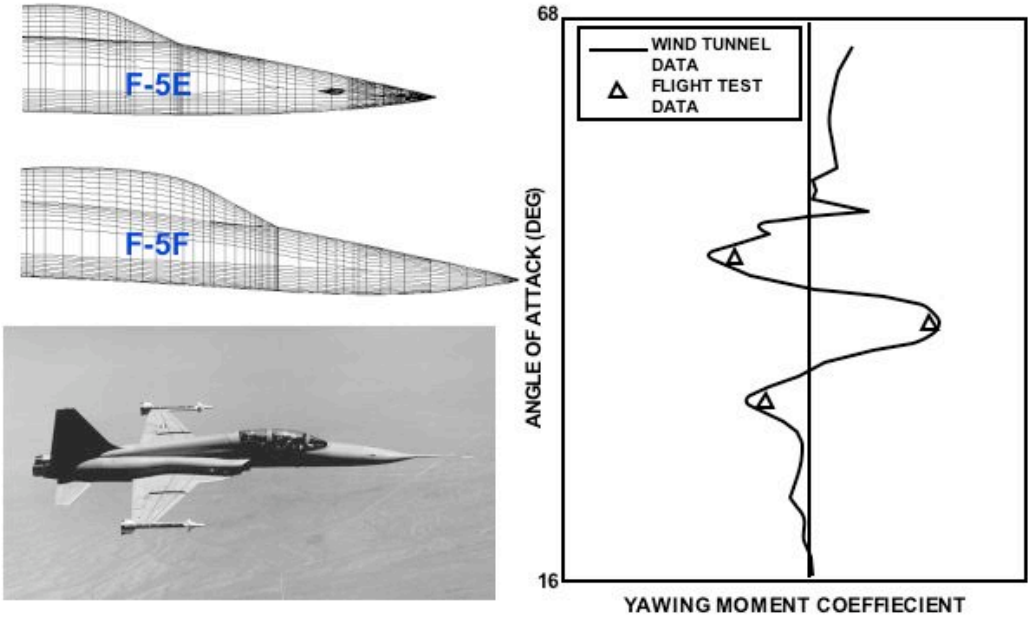
F-5F Wind Tunnel to Flight Test Correlation



Can Current CFD Predict Adequately?

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Final modifications made to the F-5F.

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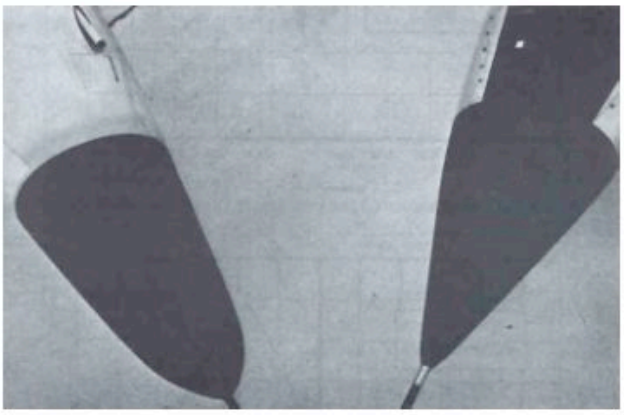
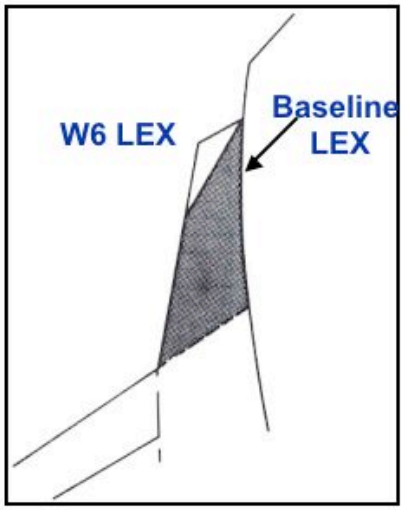
F-5F Shark Nose and W_6 LEX Modifications



Shark Nose Baseline



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NORTHROP GRUMMAN

The Shark nose eliminated the forebody vortex asymmetry.

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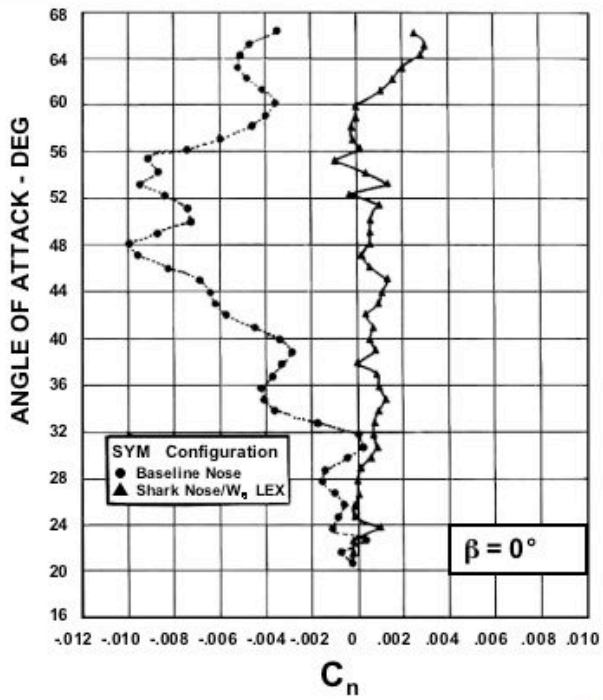
Shark Nose Effect on Aerodynamic Asymmetries



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Significantly improved directional stability to high angles. Change to LEX delayed wing stall. More elliptical forebody shape produced stable restoring moment.

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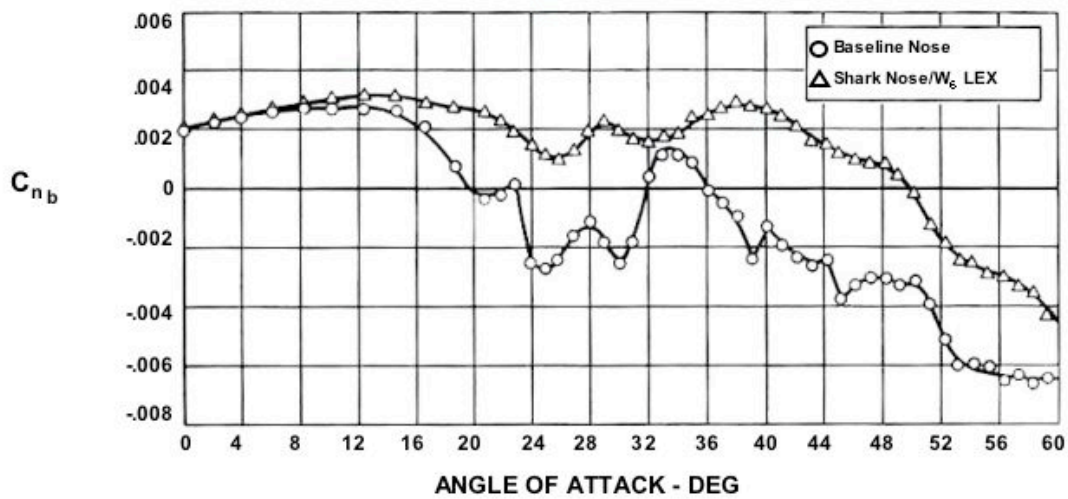
Effect of Shark Nose/W_6 LEX on Stability



Significantly Improved Directional Stability to High Angles

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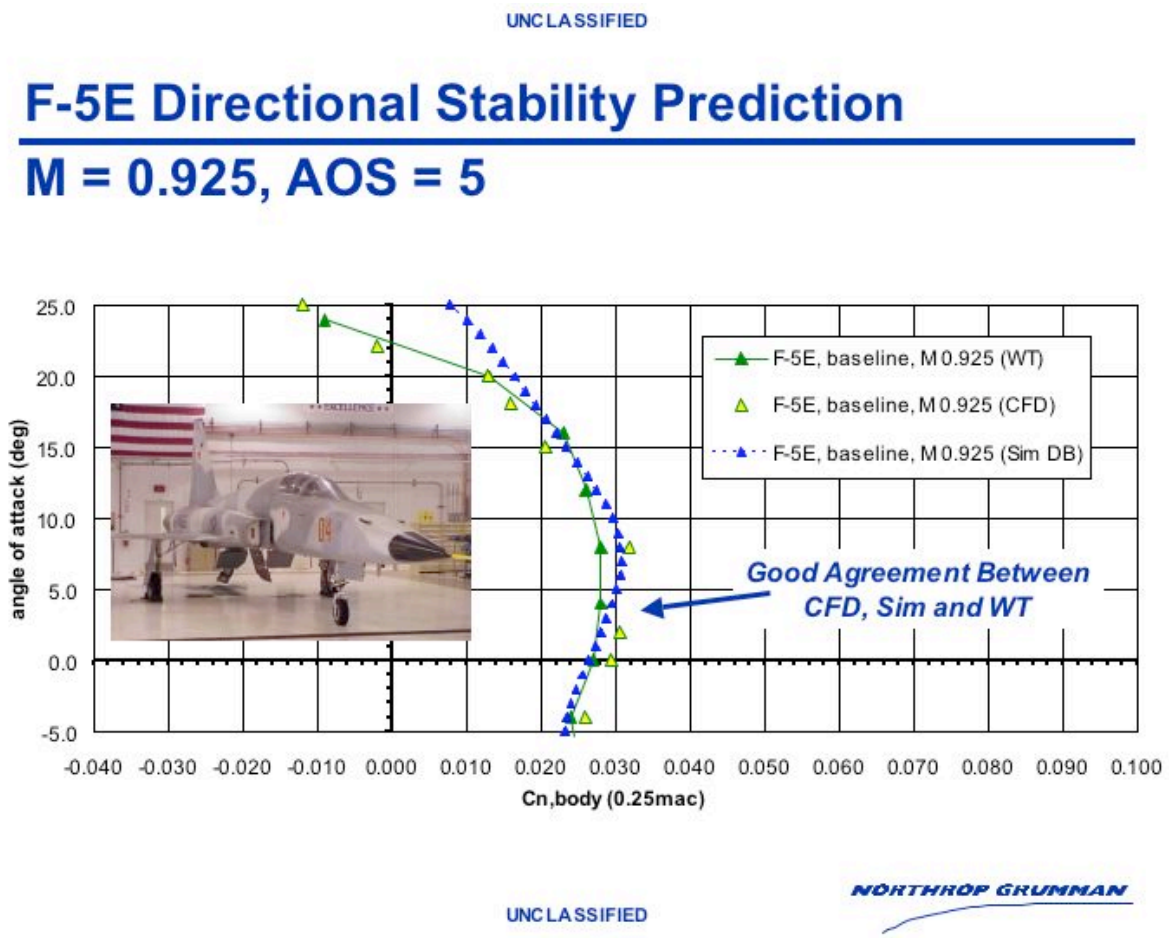
Good agreement between CFD result and wind tunnel up to 25 degrees. Good agreement between CFD result and simulation based on flight testing up to 20 degrees.



Summary

- Current CFD Methods for S&C Are
  - Used to Answer Questions About the Experimental Results
  - Used For Pre-Test Prediction With Known Limitations
  - Expected to Reduce Number of Wind Tunnel Entries and Configuration Variations
  - Able to Reduce Risk and Improve Design Cycle Time
- CFD Graphics Represents an Effective Visualization Technique for Interpreting Complex Airflows in 3-D and Aids in Flow Physics Understanding
- Need for Improved Prediction Continues as Computational Methods for Stability And Control Still Can Not Adequately Model All Cases
- Design Methods Needed on Future Military Aircraft
  - Design For Low Observablity/High Performance
  - Design of Unconventional Configurations
  - UAVs are Next Class of Systems Needing Improved Prediction

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Recommendations For COMSAC

- Need Validation Cases with Wind Tunnel/Flight Data Base in Cooperation with Ongoing Programs
- Accurate Methods Needed For
  - Unsteady Flows
  - Dynamic Derivatives
  - Aerodynamic Asymmetries
  - Hysterisis In Pitch and Sideslip
  - Vortex Decay
- Reduce CFD Uncertainty
  - Turbulence Models
  - Grid Definition
  - Reliability
- CFD Resource Requirements
  - Design Methods Needed Today
  - Data Base Generation Prohibitive

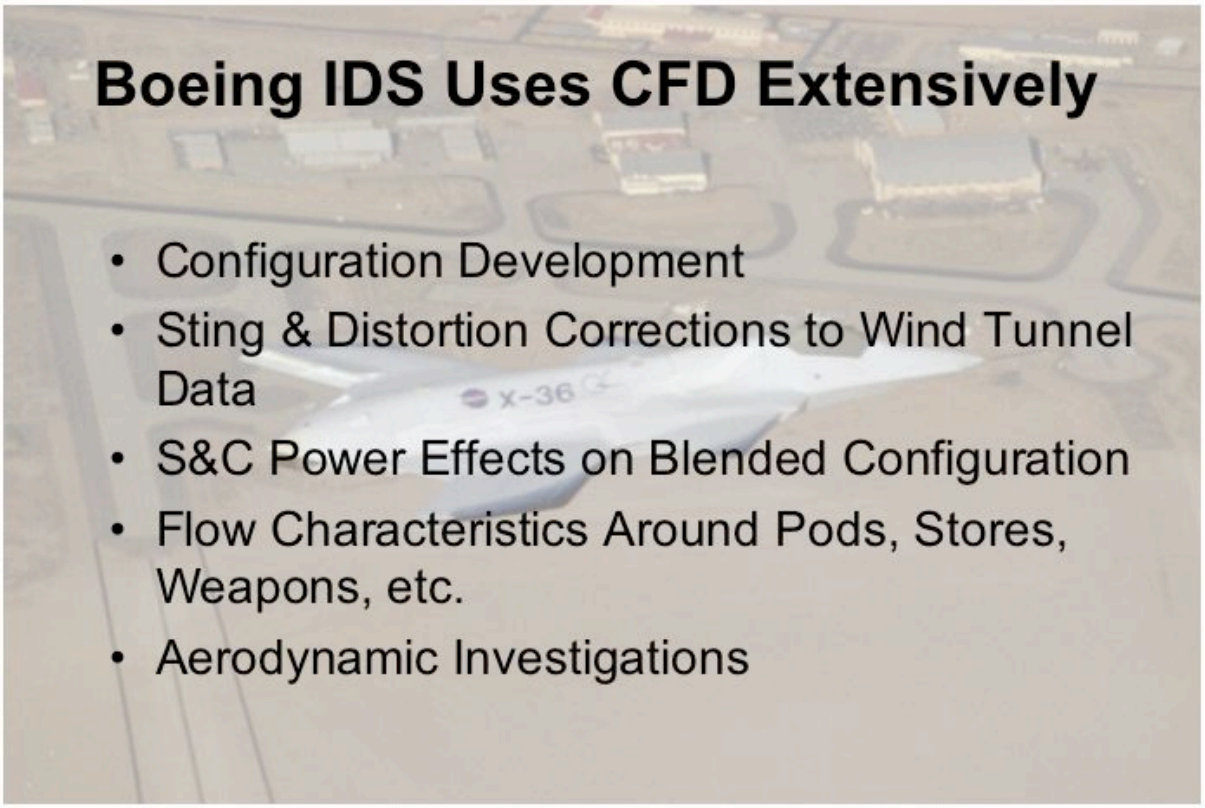
NORTHROP GRUMMAN

This presentation will discuss Computational Fluid Dynamics as it is used for tactical aircraft and weapons development. Primary emphasis will be products designed, developed and built in St. Louis reflecting the presenter's background and experience, though it is believed that similar issues will be found wherever tactical vehicles are developed.

COMSAC 23-25 Sept 2003 Boeing IDS - Dave Evans

Over the past several years, Boeing has used Computational Fluid Dynamics extensively for a variety of development and analysis tasks. In configuration development, CFD is used to direct design effort for both internal and external flow to maximize performance. Wind Tunnel distortion effects are accurately estimated using CFD. Sting and distortion testing, if it is conducted at all, is pushed of to a later part of the program. Blended configurations with embedded engines, like most of the configurations we work with, have extensive aero propulsion interaction and CFD has proven a valuable method for investigating and quantifying these interactions. Again, both internal and external flow must be modeled.

CFD has proven valuable in modeling flow around sensors, pods, stores, weapons, and weapons



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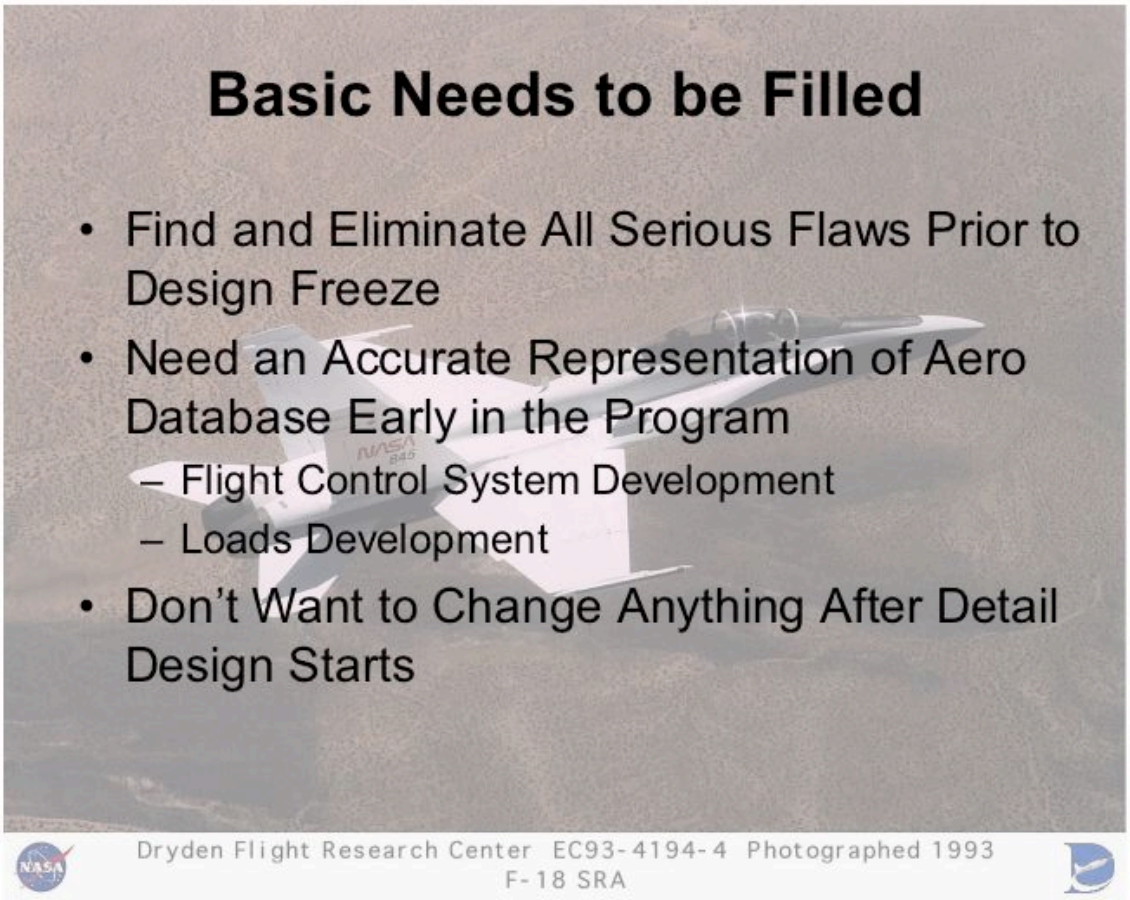
bays for a variety of uses including stability and control, sensor performance, and structural loads. CFD is a valuable tool for investigating weapon separation issues, estimating stability and control of a small vehicle embedded in the flowfield of a much larger air vehicle.

Aerodynamic investigations might include control power issues, separated flow investigations, estimating effects of external changes, and so on. All of these are very amenable to CFD analysis.

There is constant pressure from program management, both customer and company, to shorten development time and reduce costs. Wind tunnel testing is both costly and time consuming and may prove inaccurate due to geometry inaccuracies and Reynolds Number scaling effects that are hard to predict. Yet it is critical to fully investigate a configuration, eliminating flaws prior to design freeze because it is terribly expensive to change anything later in the program. Once the design is frozen, design loads are required to begin detail design. In a highly maneuverable vehicle maneuvering inertia loads are often as high or higher than air loads. Therefore, a fairly detailed concept for the flight control system, necessitating a detailed and accurate aero database, are required to develop credible loads. CFD should play an increasing role in this development. Accuracy is important because of the expense of redesign late in the program.



The presenter anticipates others will speak of need for analysis at cruise conditions and for low speed, high lift configurations. That is important for tactical vehicle too, so chalk up another "yes" vote for these capabilities. However, many critical design points and most of our problem areas involve massive separation on the air vehicle. We need to predict these flow characteristics.

For instance, both F-15 and F-18 aircraft have design points at or near max sustained load factor at which the wing shows significant separation. Max instantaneous turn rate, at maximum lift, is also a significant parameter in close in combat. An important point for UCAV is nose down pitch capability at high angle of attack. Weapons typically turn at very high g's and have

significant separation. A max range JDAM trajectory puts it at maximum lift for most of the flight. All of these conditions are legitimate design points and will require that accurate CFD solutions be available rapidly during the design phase through operational phase of these programs.

Damping derivatives at all angles of attack are important. Low angle of attack and high speed often set the control system capabilities. Cross wind landing in the high lift configuration depends on reasonable estimates of damping in all three axes. Departure and spin resistance as well as spin recovery estimation depends upon both forces and moments as well as damping coefficients at very high angles of attack and at high rates.

While tactical vehicles generally are designed with very strong structures, the also fly at very high speeds. Flexibility effects at high dynamic pressure severely reduces control power. We need to be able to estimate these effects far better than we can today. In particular, if we are to make use of the flexibility, as we are in the Advanced Aeroelastic Wing program, it is imperative

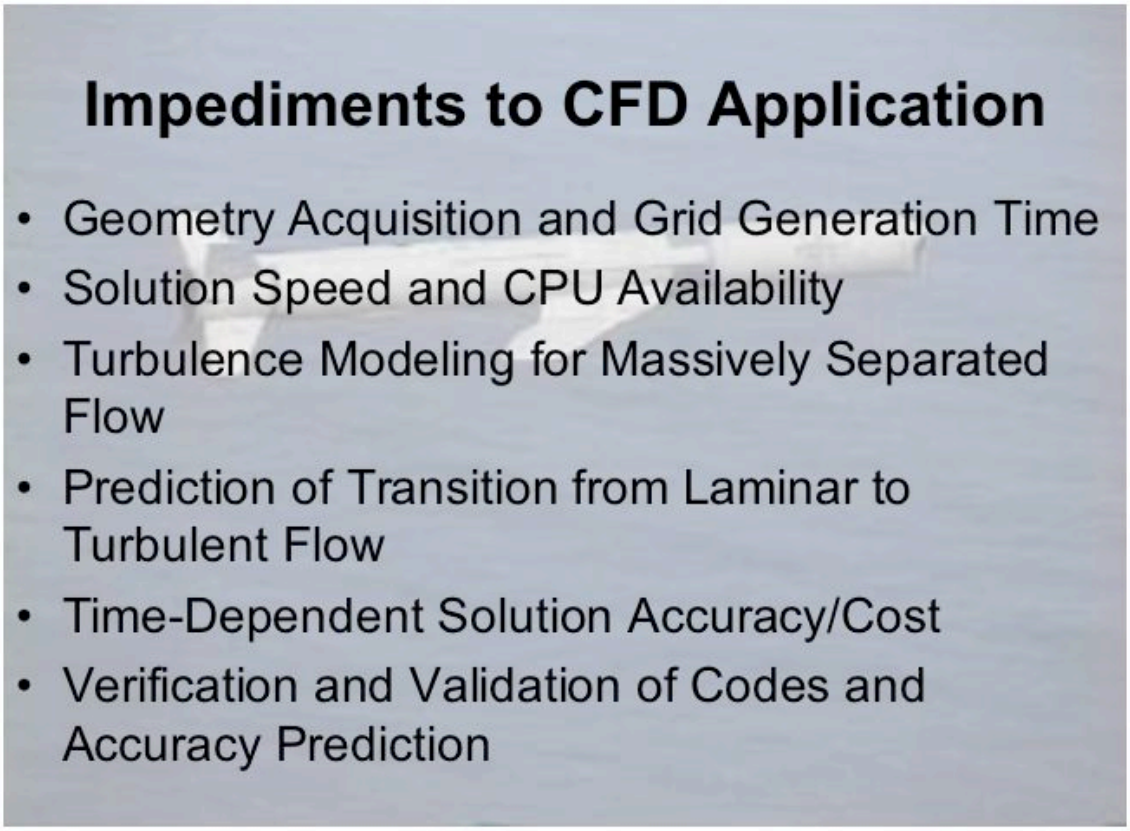
that we be able to combine CFD with structural analysis codes to predict and then to design in favorable aeroelastic behavior.

Weapons influence on the parent airframe and that airframe influence on weapon separation are also extremely important for tactical vehicles. After all, the main job of the aircraft is to get the warheads and sensors out to the battle where they can do their job. Safe and effective separation cannot be overemphasized and it should be designed in from the beginning of the program.

Much has been said over the years and probably en this symposium about the first four items on this lest. I Probably can't add anything to the discussion that has not been said.

Time dependent solutions are possible and will become more necessary as they get more possible with increased speed of solutions. There are many applications waiting, dynamic lift effects, transient internal and external flow phenomena, and weapon separation to name but a few.

Finally, verification and validation of CFD codes and applications is extremely important. The codes themselves should be verified and validated, but perhaps it is even more important to verify and validate the application of the code. Improper preparation, faulty assumptions, and



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schedule pressure cause perfectly good codes to give the wrong answer with great precision. As an industry we cannot afford to be led astray by our trusted tools.

NASA COMSAC Symposium

Computational Methods in Stability and Control – WPAFB Perspective

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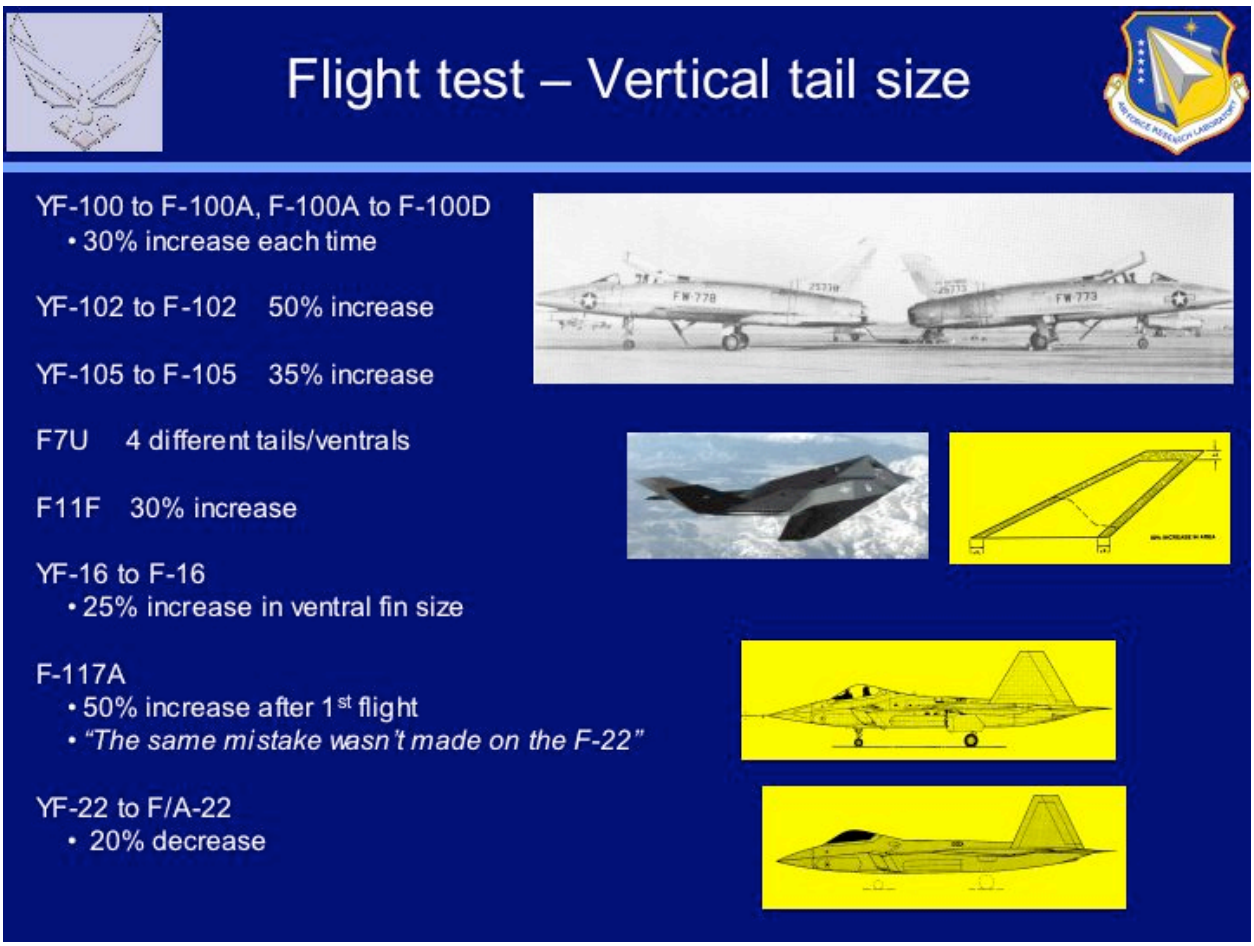
Outline

- S&C problems in flight test
- USAF needs/Current practices
- What CFD needs to demonstrate

Getting the vertical tail size correct on the first try has been a challenge for over 50 years. Most of the Century Series fighters suffered from roll coupling brought on by a combination of high rates of roll and insufficient stability to counter the resultant buildup in alpha and beta. Enlarging the vertical tails was the most common and successful solution.

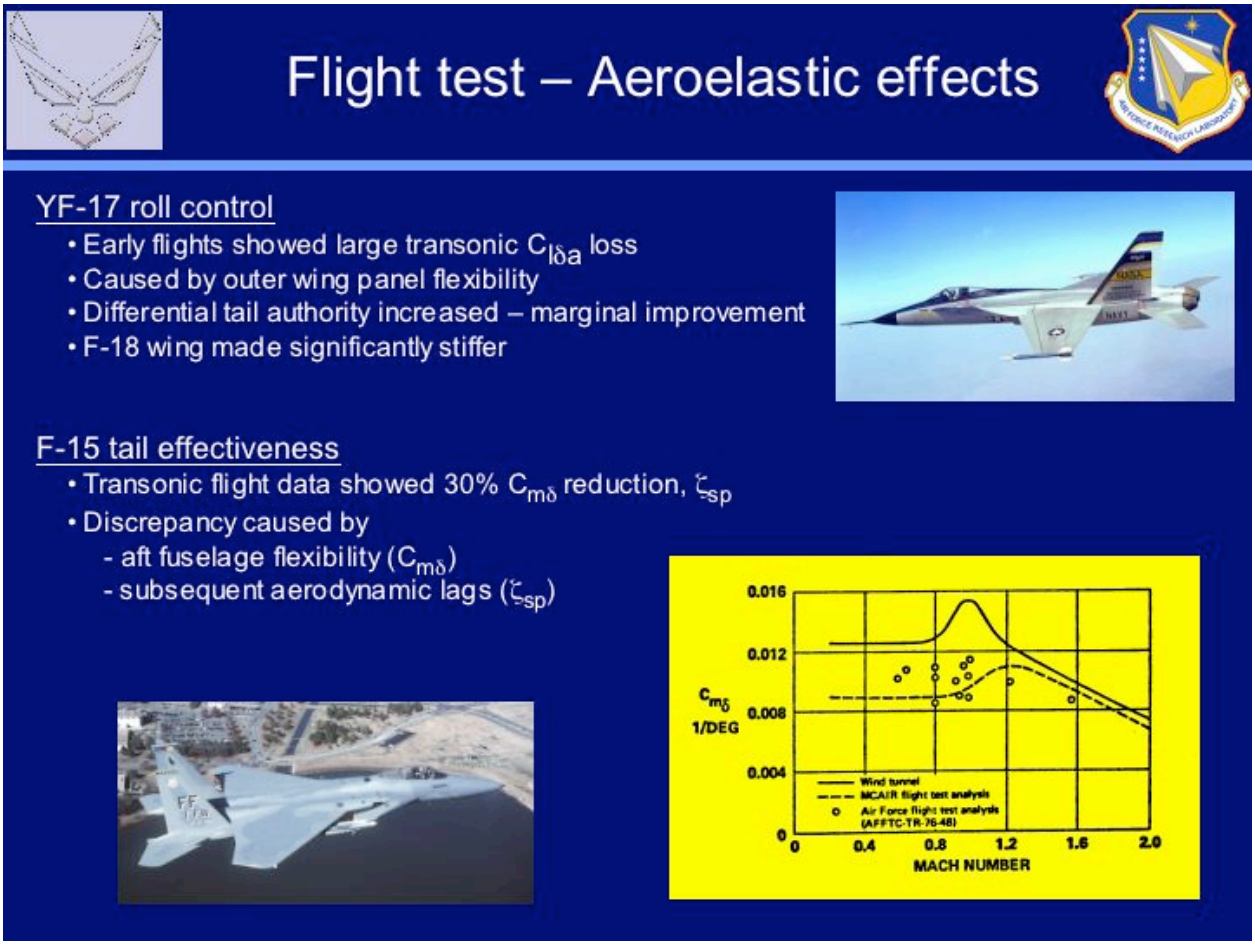
Early tests of the "Have Blue" stealth prototype with its inward canted vertical tails proved unsatisfactory, so outward canted tails were selected for the F-117A. Even so, on the first flight of the F-117A (6/18/81), directional stability and control were both found to be far less than predicted, so the tails were increased in size by 50%. Dick Abrams, head of flight test at Lockheed, stated that "the same mistake wasn't made on the YF-22". On the YF-22, several



methods were used to predict the required vertical tail size and the largest value was used with an additional safety factor included. No problems were encountered during flight test and the tail size for the proposed production configuration was actually decreased in size from the prototype.

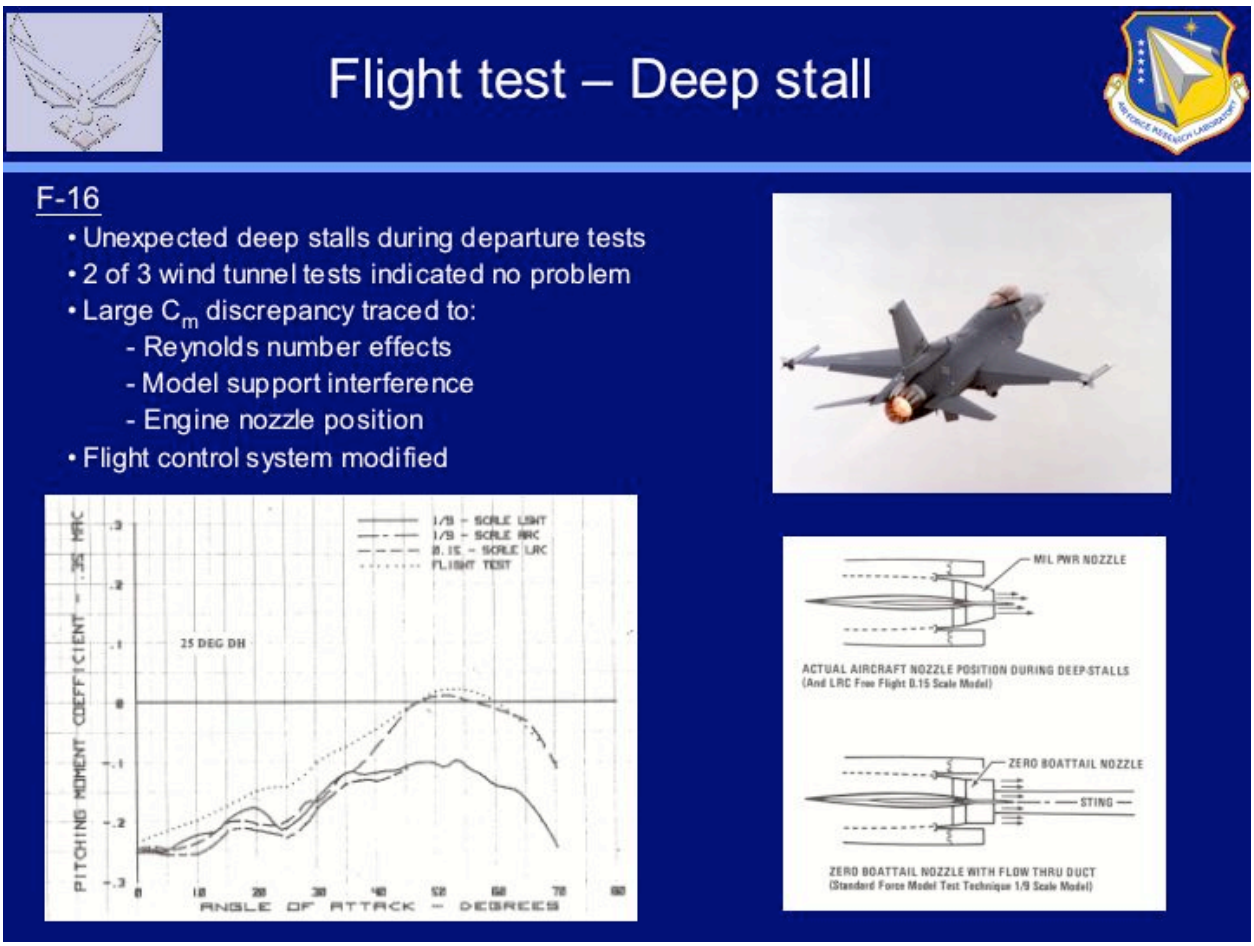
In the early 1970's, the F-15 and YF-17 suffered from reduced control effectiveness due to aeroelastic effects. In the case of the YF-17, the effect had been predicted but not the magnitude, for the F-15, the effect had not been predicted.

Early flights of the YF-17 showed unsatisfactory roll performance at high dynamic pressure conditions, a problem that was traced to excessive wing flexibility which reduced aileron effectiveness. Aileron and differential tail authority were increased but both were hinge moment limited so the final roll performance was still less than desired. The wing of the F-18 was made significantly stiffer to avoid a similar problem.



Maximum load factor attained in high-g pullups of the F-15 was found to be less than predicted at transonic speeds. In addition, the short period damping was found to be underpredicted although the short period frequency matched predictions. An aeroelastic analysis showed that aft fuselage bending reduced the tail effectiveness while a dynamic time lag between the fuselage and build-up in lift of the tail reduced the short period damping. Due to its abundance of control authority, neither problem degraded operational effectiveness.

During departure tests of the F-16, deep-stall trim conditions were encountered at + and – 55 degrees angle of attack. Although the possibility of a deep-stall had been considered, none was expected at the c.g. locations where the flights were conducted. Analysis of the data indicated a major pitching moment discrepancy between the wind tunnel predictions and flight. High angle of attack tests had been conducted in four facilities. A detailed study of the results from these and other tests indicated that Reynolds number effects, model support interference, and the engine nozzle position were the major contributors to the discrepancy. This study was conducted in the early 1980's and CFD was not used as a diagnostic tool.



A wind tunnel test of the F-15 STOL and Maneuver Technology Demonstrator (SMTD) in ground effect was conducted at the McDonnell Low Speed Wind Tunnel. A fixed ground board with no boundary layer removal system was used. Cold jet thrust reversers were used. The results showed a large plume induced pitchup which increased with sideslip. The control laws were modified to prevent a tail strike during landing. A later test with a model was conducted at the Langley Vortex Research facility. This test indicated virtually no plume induced pitching moment change. Excessive nose down moments were apparent in early flight tests that almost bottomed the nose gear. Analysis of the flight test data indicated a plume induced nose down moment, different from both tunnel tests but closer to the Langley results. The flight control laws were modified and future tests were completed without incident. At the time of this problem (early 1990's) CFD was too immature to tackle this type of analysis.

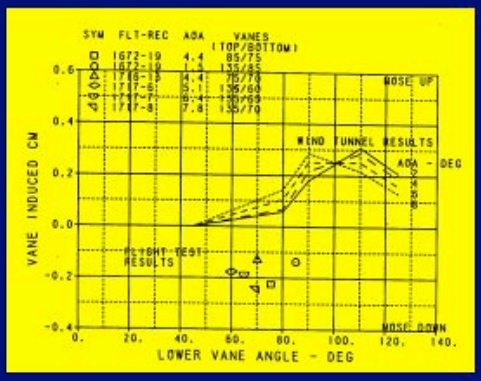
Flight test – Ground effects

F-15 SMTD with reverse thrust

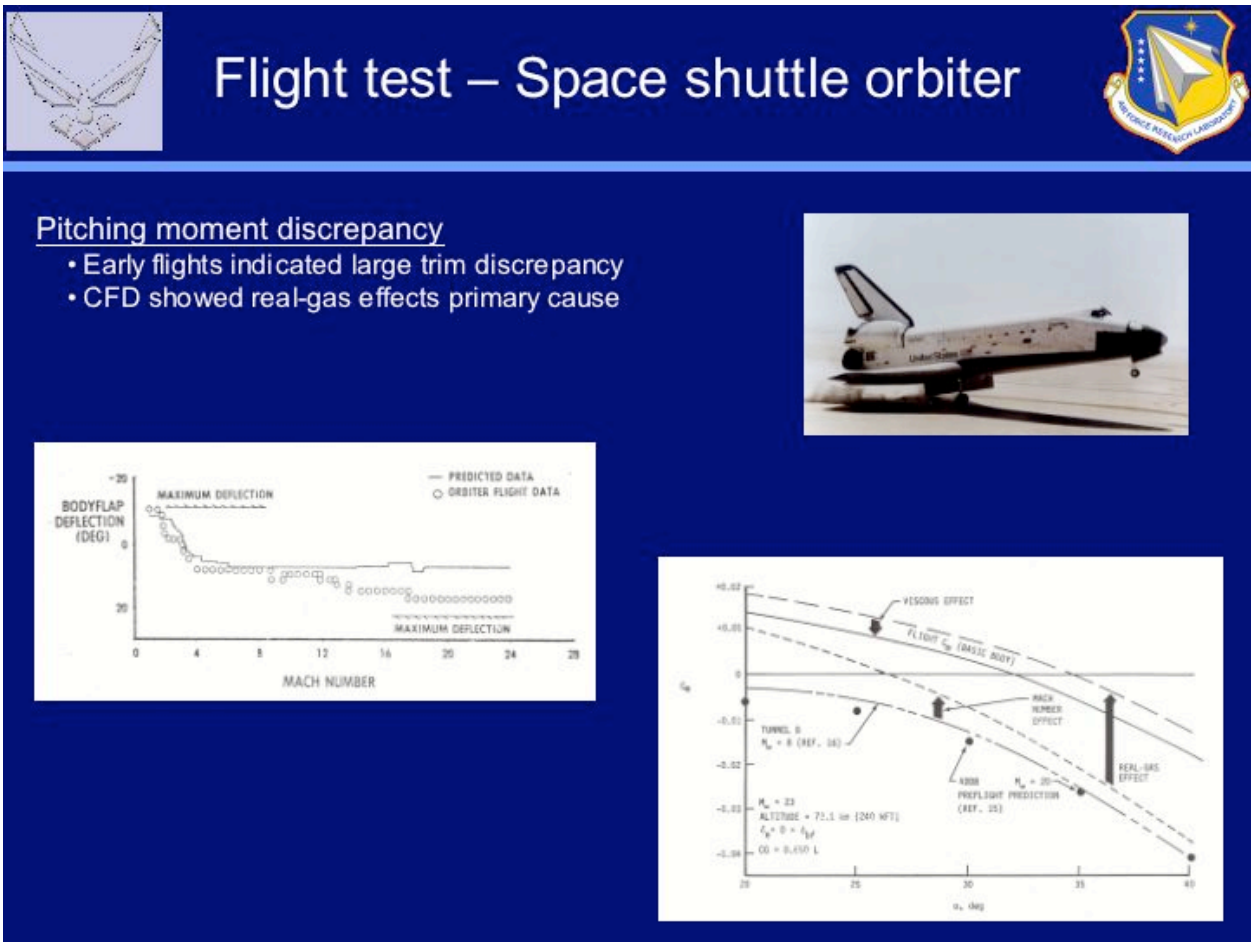
- Wind tunnel test at McDonnell LSWT
  - fixed ground board
  - strong plume induced pitchup
- Control laws modified – nose down canard bias
- LaRC VRF moving model test showed different result
  - too late to impact flight test program
- CFD solutions not attempted

Flight test experience

- Excessive nose down moments in early flights
- ~20 deg/sec nose down pitch @ landing
- Analysis indicated large Cm discrepancy
- Flight control system modified



Almost 30,000 hours of wind tunnel testing for aerodynamics/S&C were conducted on the Space Shuttle. The vast majority of this data is for Mach<8. At higher speeds, the limited data available were corrected for viscous interaction and aeroelastic effects analytically. No corrections were made for real gas effects. Early flight showed large discrepancies in the predicted trim settings of the body flap and elevons. Analysis of the data indicated an error in predicted center of pressure of approximately 1% body length (2% m.a.c.) for M>10. Extensive calculations using CFD were conducted to study the discrepancy. These indicated that the primary contributor was real gas effects, with Mach number effects and viscous effects also playing a role.



The F/A-22 and V-22 both suffered from tail buffet caused by unsteady vortex effects emanating from the LEX (F/A-22) and forebody (V-22). In both cases, extensive flight tests and CFD analyses were conducted. Actively controlled rudders were briefly considered as solutions in both cases. For the F/A-22, the problem was solved with an internal structural modification. For the V-22, a large fixed strake was added above each door.

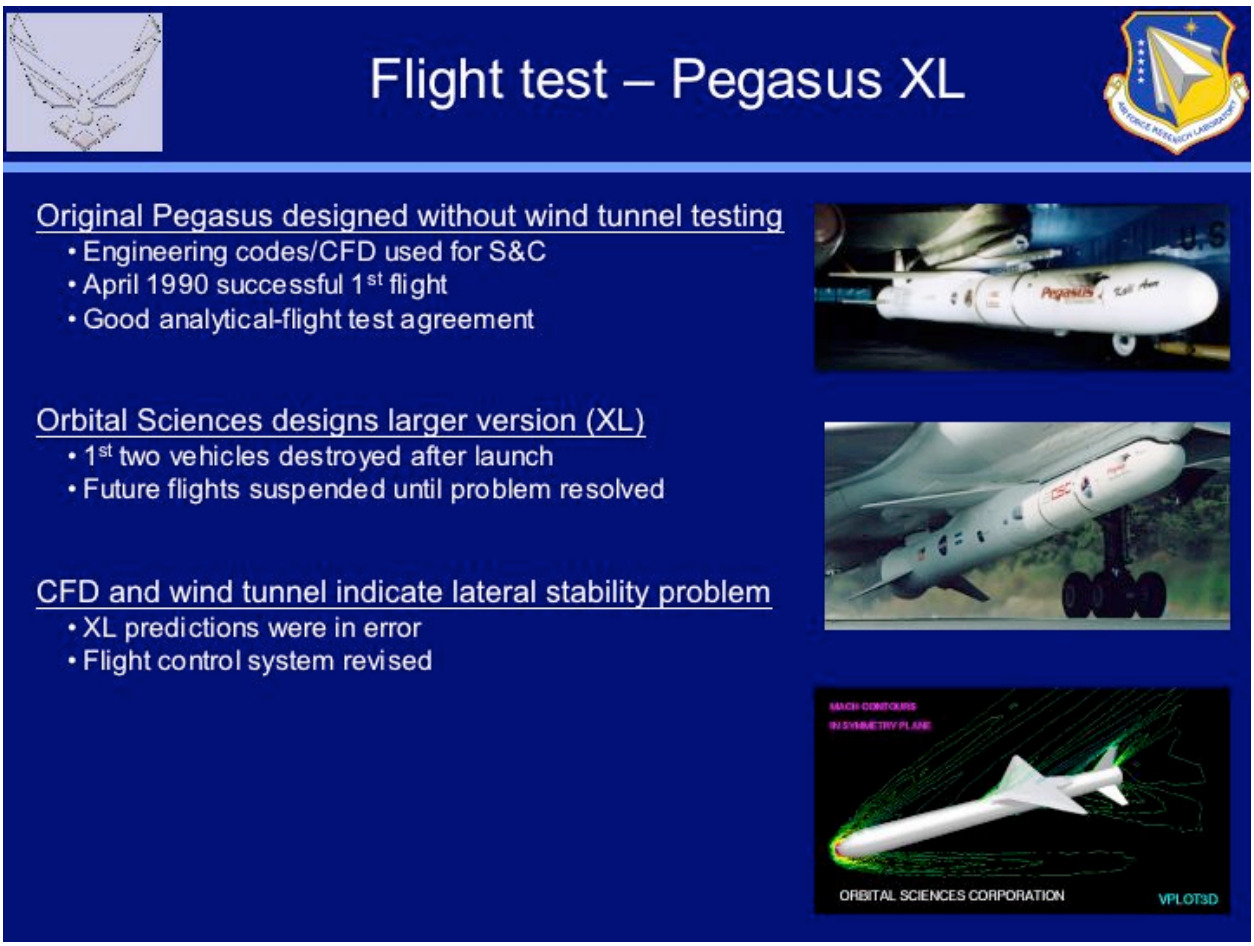
Flight test – Tail buffet

Problem not unique to the F-18

F/A-22
- Caused by LEX vortex
- Extensive flight tests/CFD analysis
- Minor structural beefup

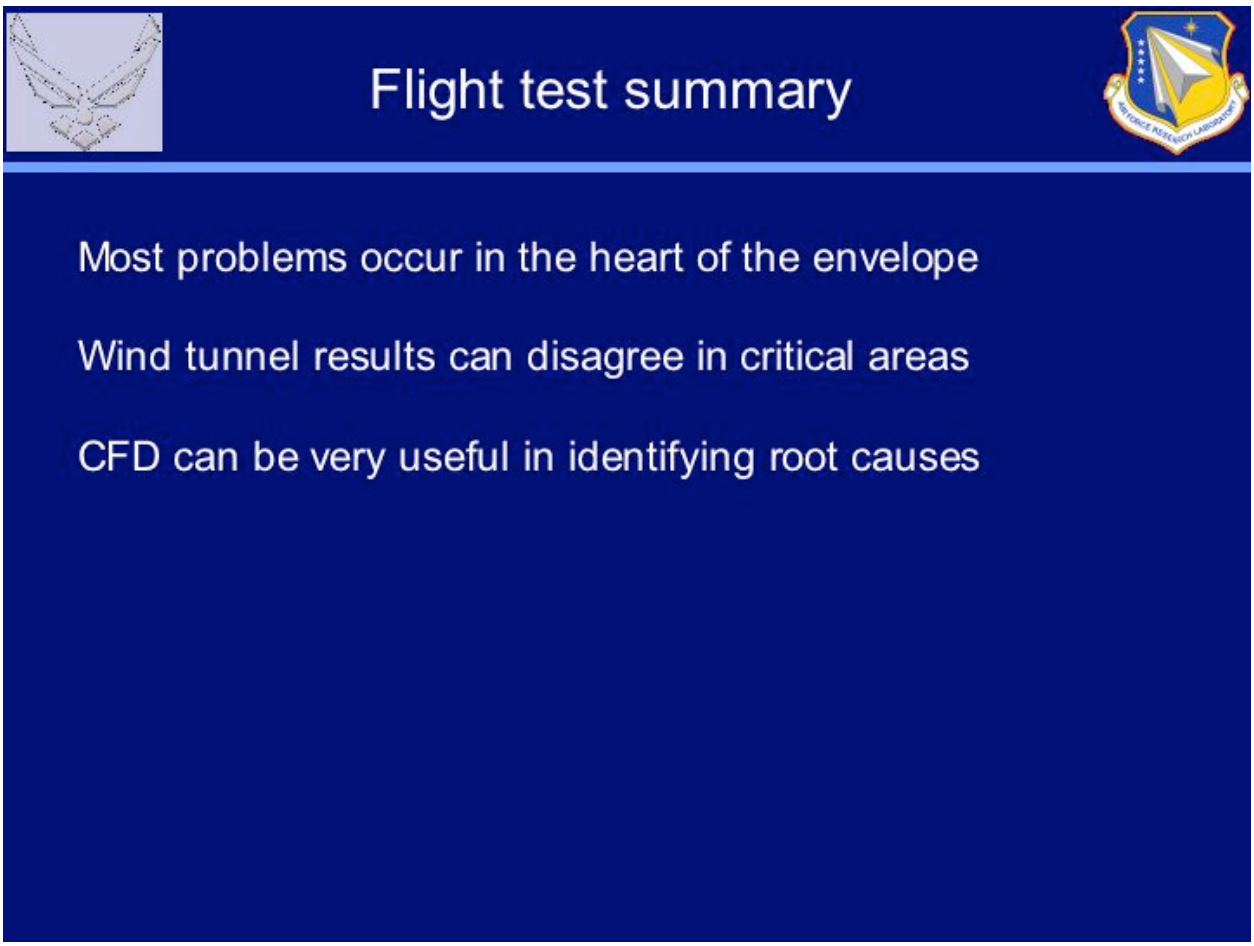
V-22
- Caused by forebody vortex
- Extensive flight tests/CFD analysis
- Large strake added above door

The Orbital Sciences Pegasus booster was designed without wind tunnel tests. Engineering level codes and a limited amount of CFD (see AIAA paper 91-0190) were used for aerodynamics and stability and control. Good agreement between predictions and flight test were found (see AIAA paper 93-0520). A larger vehicle, Pegasus XL, was designed with a longer fuselage, higher mounted wing and modified tails. The first two flights of the XL version (June 94, June 95) ended in failure after the booster had to be destroyed. For the first time, wind tunnel tests were conducted, along with CFD analyses. These showed that lateral stability was not well predicted for XL version. The flight control system was modified and successful flights resumed in March 1996.



Except for the F-16 deep stall, all of the flight test problems discussed in this presentation occurred in the heart of the flight envelope. This is also true for other problems discussed in this conference such as the F-18 “wing drop”.

Resolving differences in wind tunnel results can be very important. This is definitely an area where CFD can contribute.

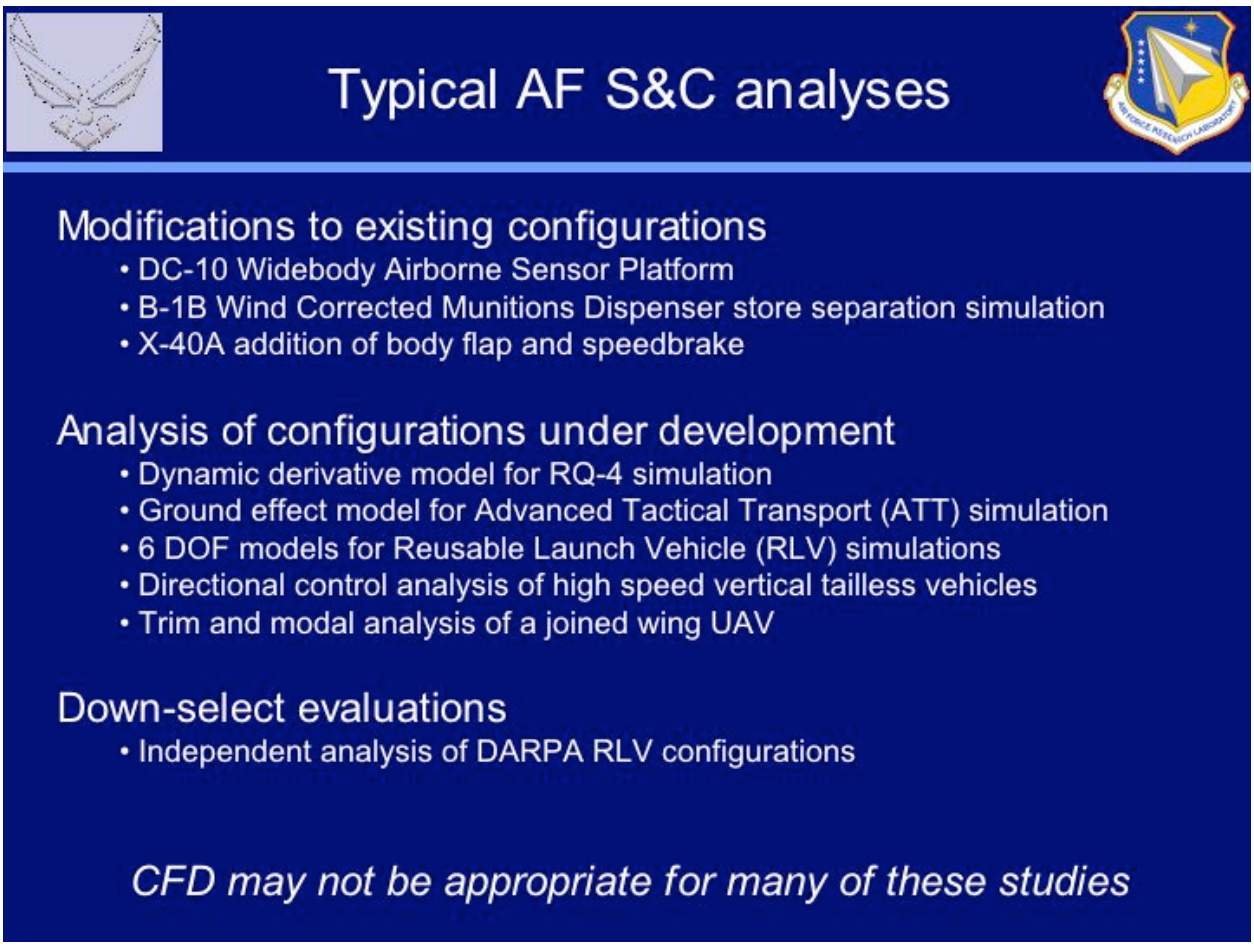


Outline

- S&C problems in flight test
- USAF needs/current practices
- What CFD needs to demonstrate

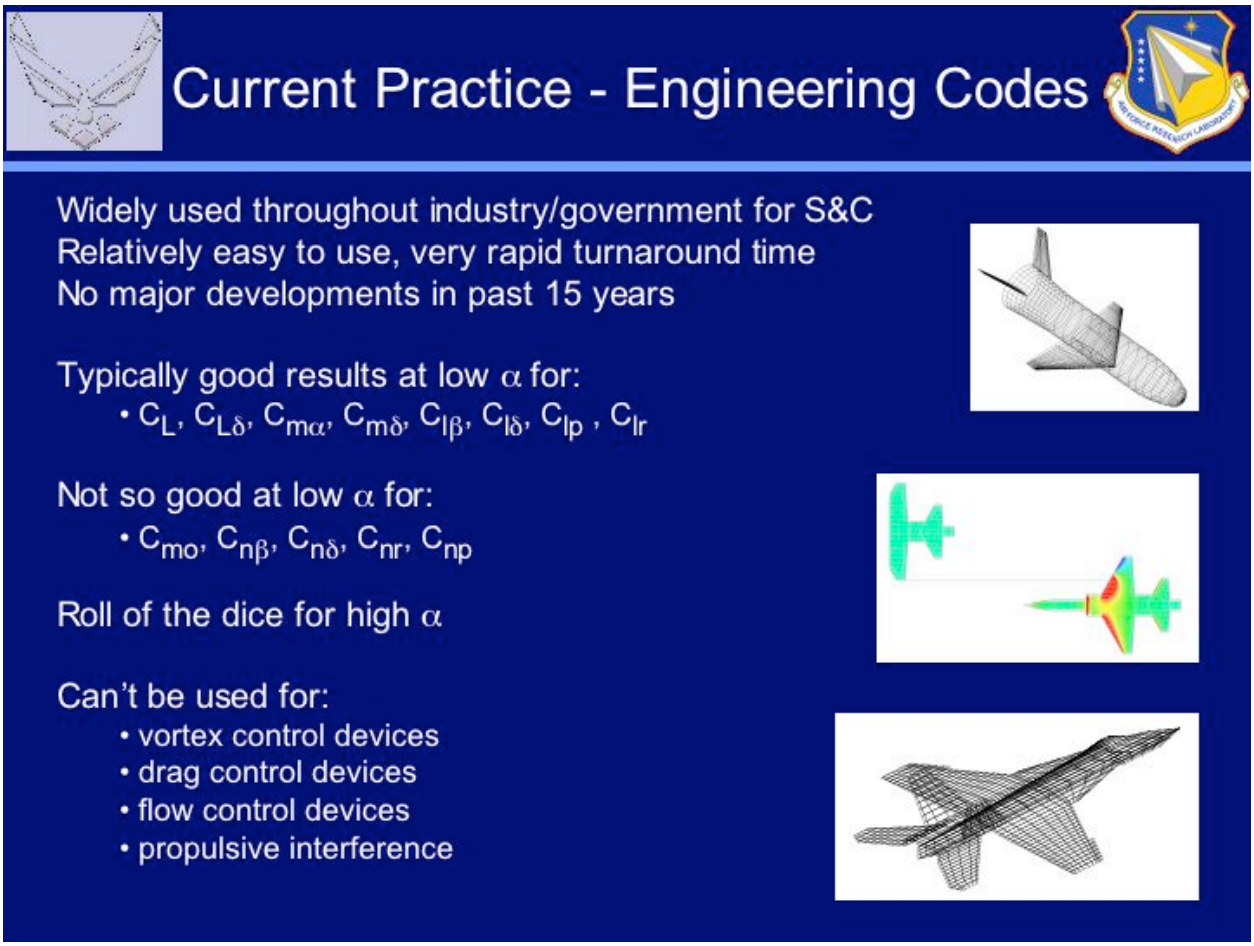
Typical S&C analyses done by AFRL or ASC fall in three general categories. Examples are shown which occurred over the past 12 months. In many of these cases, short time lines were involved.

CFD was used to a limited extent for the first two items only (DC-10, B-1B). In all other cases, engineering level codes or wind tunnel results were used. In many cases, use of CFD would be overkill. AFRL is somewhat atypical in that most programs involving any S&C analysis are at the early conceptual or preliminary design stage. Most analysis of fielded systems is done within ASC.



Engineering codes are defined here as Datcom-type semi-empirical codes, vortex lattice codes and inviscid 3-D panel codes. These are still the standard in both industry and government for generation of S&C data bases. There have been no major theoretical developments for this class of codes for the past decade. Most improvements have come in the form of graphical user interfaces and including the codes within larger design synthesis tools. While this latter "improvement" definitely increases productivity, it also increases the chance for GIGO as these tools become more "black box" in nature.

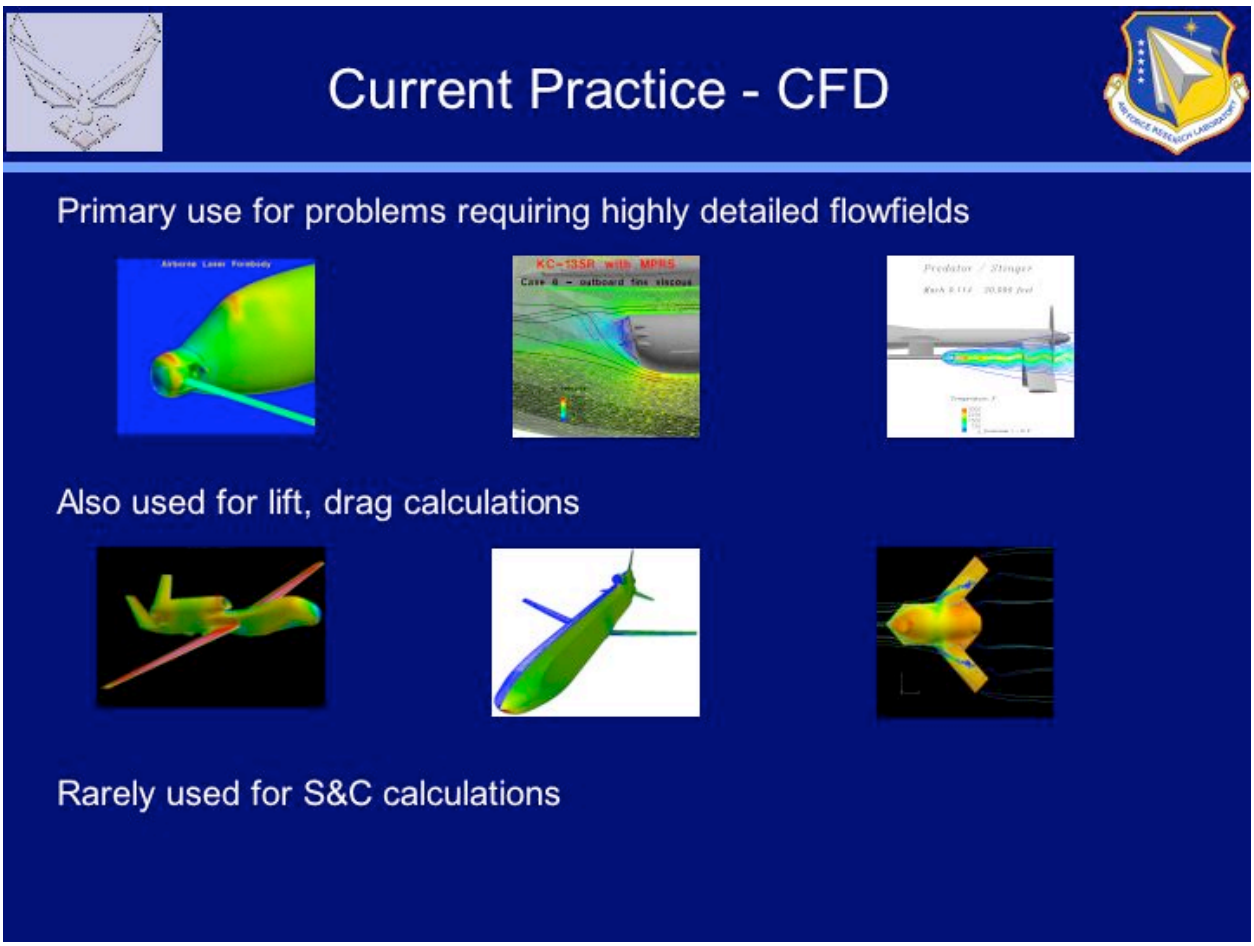
While engineering codes typically give good results at low angles of attack for many parameters, others such as pitching moment at zero angle of attack are very difficult to predict. Accurate



values of Cmo are also difficult to get from a wind tunnel. Many of the yawing moment parameters are also difficult to predict (primarily for vertical tailless vehicles). In addition, these codes are of little or no use for separation based control devices or aero-propulsive interference effects. Ground effect are also difficult to predict.

Most CFD calculations within AFRL and ASC are geared towards problems requiring highly detailed flowfields. Problems shown here are: optical distortion of the airborne laser due to the forebody flow of the aircraft; hose oscillation behind the KC-135R multi-point refueling system pod; and plume impingement from a Stinger missile on the tail of a Predator UAV. Lift and drag calculations are also done using CFD. Problems shown here are: laminar flow investigation on the Global Hawk; transonic performance on the ALCM; and an X-45A computation that was done in concert with a wind tunnel program.

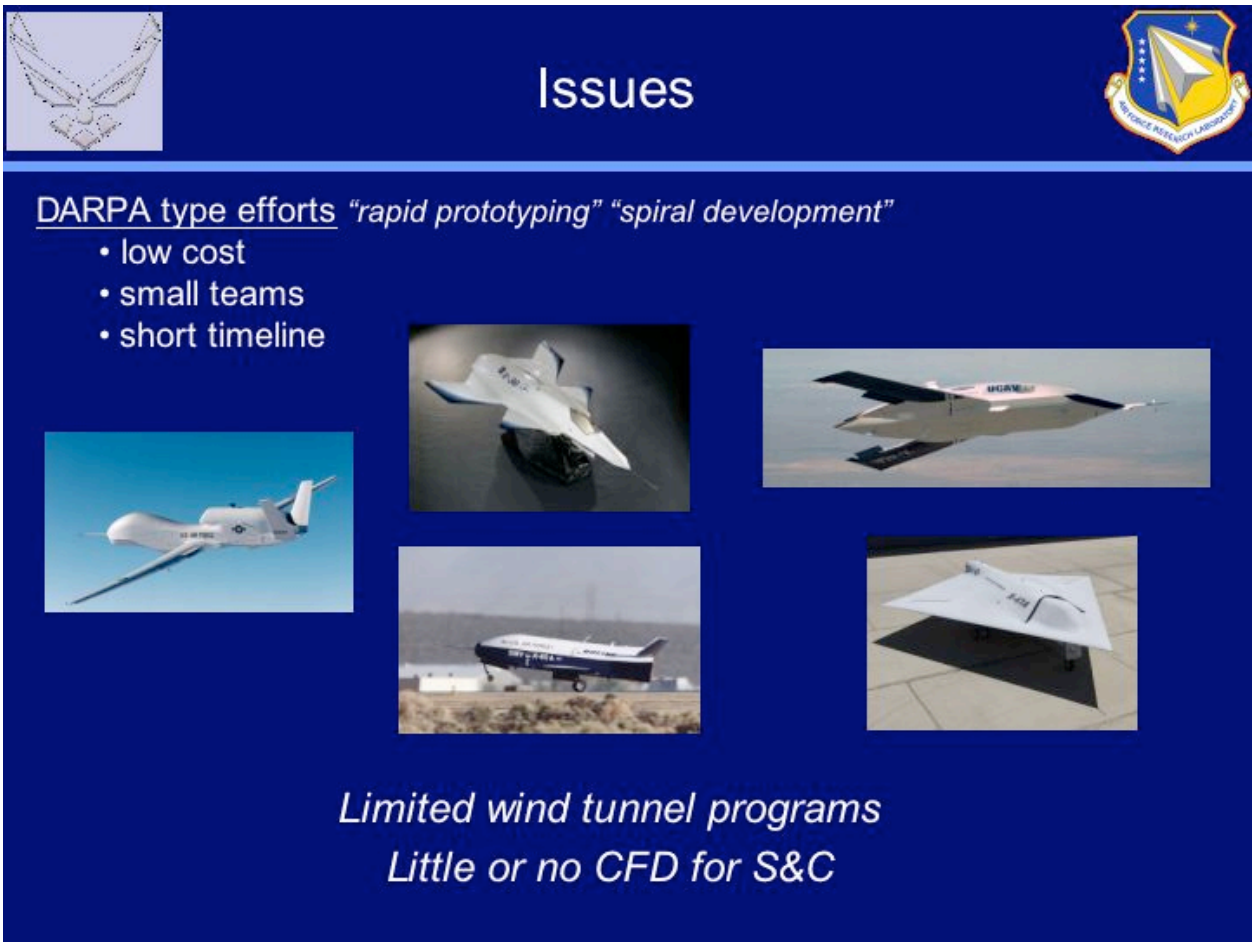
CFD is rarely used for S&C calculations within AFRL or ASC. For the DC-10 WASP problem discussed previously, contractor CFD calculations were performed. For the B-1B WCMD



problem, prior CFD calculations from AEDC for the B-1B with weapons bay doors open were used to generate a data base of local flow conditions to put into a store separation simulation.

One impediment to use of CFD for S&C on future programs is the trend away from large development programs (F-22/V-22/JSF) towards low budget demonstrators with potential production at a future date. These programs typically operate with tight time constraints and very low budgets.

The X-40A program is typical. It is a subsonic Space Maneuver Vehicle technology demonstrator that was airdropped from a helicopter and autonomously flown to the landing site. It was completed in 36 months for less than $20M. The aero/S&C analysis consisted of an engineering code (APAS) and two wind tunnel entries, a configuration development test in a



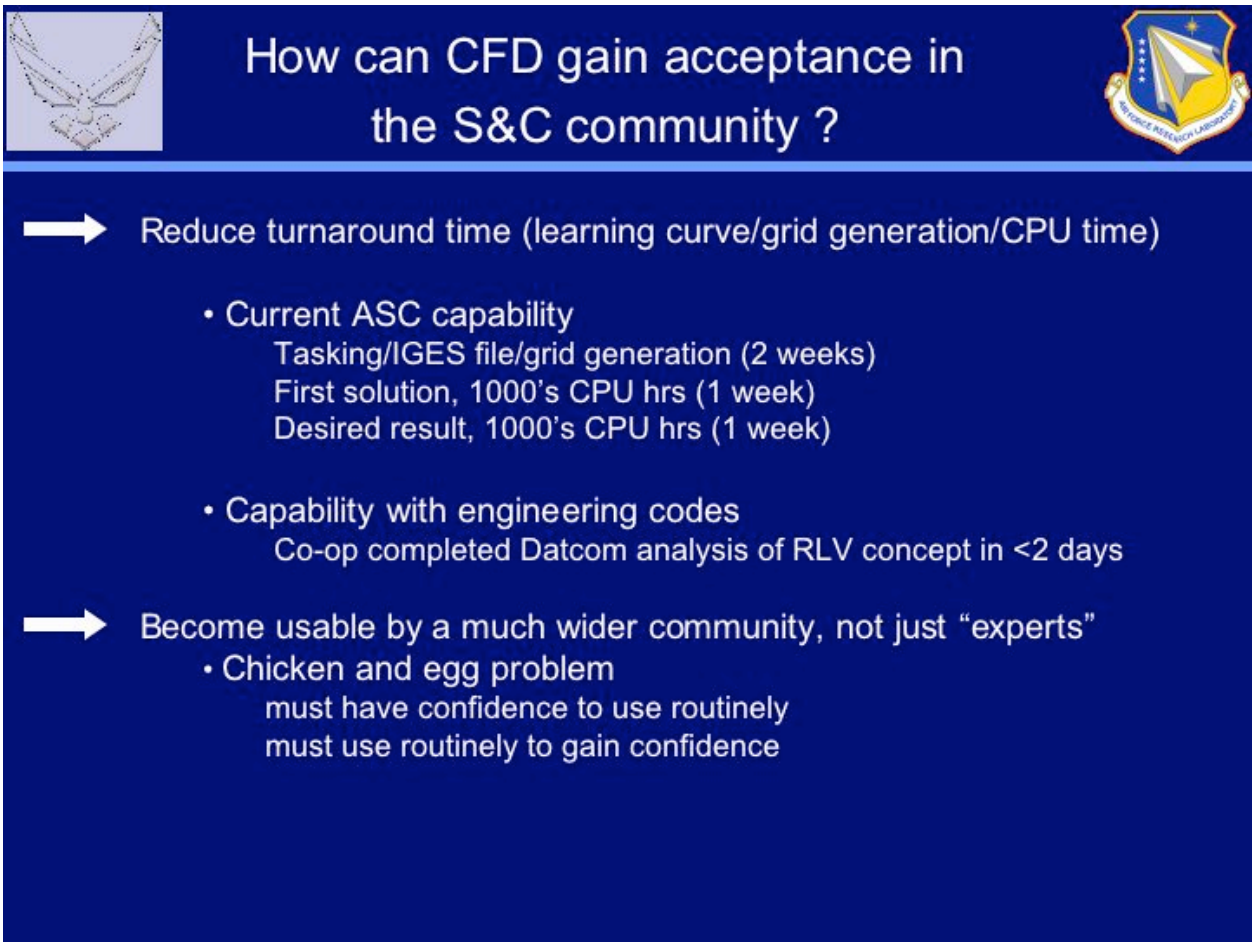
very small facility and a data base test on the final configuration in an 8x12 ft low speed facility. No CFD was done at low speeds for aero or S&C (some CFD was done to assess hypersonic characteristics).

Outline

- S&C problems in flight test
- USAF needs/Current practices
- What CFD needs to demonstrate

This chart shows the major impediments to CFD use in S&C at WPAFB. Turnaround time has always been a problem but has shown steady improvement with unstructured grids and advances in computational power. The ASC capability shown represents a complete configuration analysis using the Navier Stokes solver COBALT. Continually changing configurations during design also hampers the utility of CFD.

The second issue is somewhat of an organizational problem. The "CFD" branch within AFRL is an isolated entity which typically support projects that are externally funded. In a 1999 downsizing, AFRL management declared "stability and control is a solved problem" and



abolished the stability and control group. CFD related S&C efforts (high angle of attack dynamic derivative computations) ceased and the eight remaining "S&C" engineers now reside within five different branches.

Where can CFD best be used ?

Develop methods to scale/check wind tunnel data

- Currently, gathering wind tunnel data for extensive S&C database is cheaper and faster than using CFD
- To save cost and schedule (due to very large S&C database) virtually all S&C wind tunnel data is gathered at low Reynolds numbers
- If strategic methodologies can be developed to check and/or scale wind tunnel data/results, substantial efficiencies can be realized

→ *Scale wind tunnel results to flight Reynolds number*

→ *Match wind tunnel/CFD results to resolve tunnel-to-tunnel differences*

→ *Fill in gaps in wind tunnel data base*

There are many problems that are difficult and/or very expensive to wind tunnel test, for which engineering level codes are completely inadequate. Two are shown here. These should be areas ripe for CFD.

Propeller effects are once again of interest. Slipstream effects for both STOL and VTOL configurations are both difficult to predict and expensive to measure. Although semi-span tests are efficient from a cost point of view, they only give half of the answer. CFD developments in the rotary wing community that should be of some use here. There has also been a loss of corporate memory both in government and industry regarding propellers (there was a Propeller Laboratory at WPAFB in the 1950's).

Ground effects for both STOL and VTOL vehicles have always been difficult to predict. Boundary layer removal has always been a key problem, moving ground belts are notoriously difficult. CFD work that has been done in this area with impinging jets has demonstrated that half-span analyses give incorrect results due to significant mixing and that turbulence modeling is critical.

Conclusion

Engineering codes still the standard for S&C computations

CFD use in S&C typically after problems in flight test

CFD must become more user friendly

Raytheon
Aircraft Company

Perspective:
Raytheon Aircraft Company

Neal Pfeiffer
Dana Herring

Date September 23, 2003

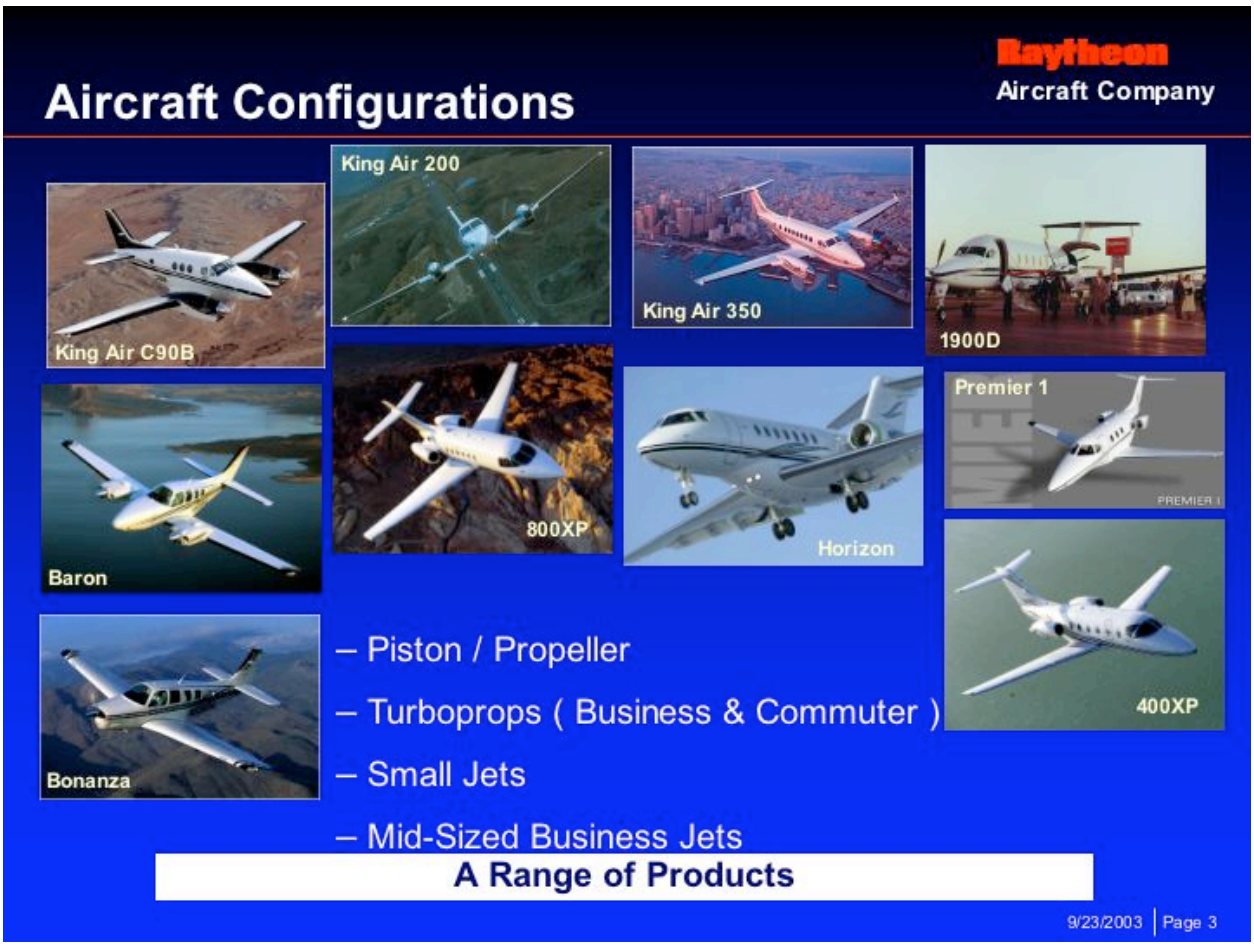
Raytheon
Aircraft Company

Introduction

Raytheon manufactures a range of business aircraft. These are sold under the Beechcraft and Hawker badges.

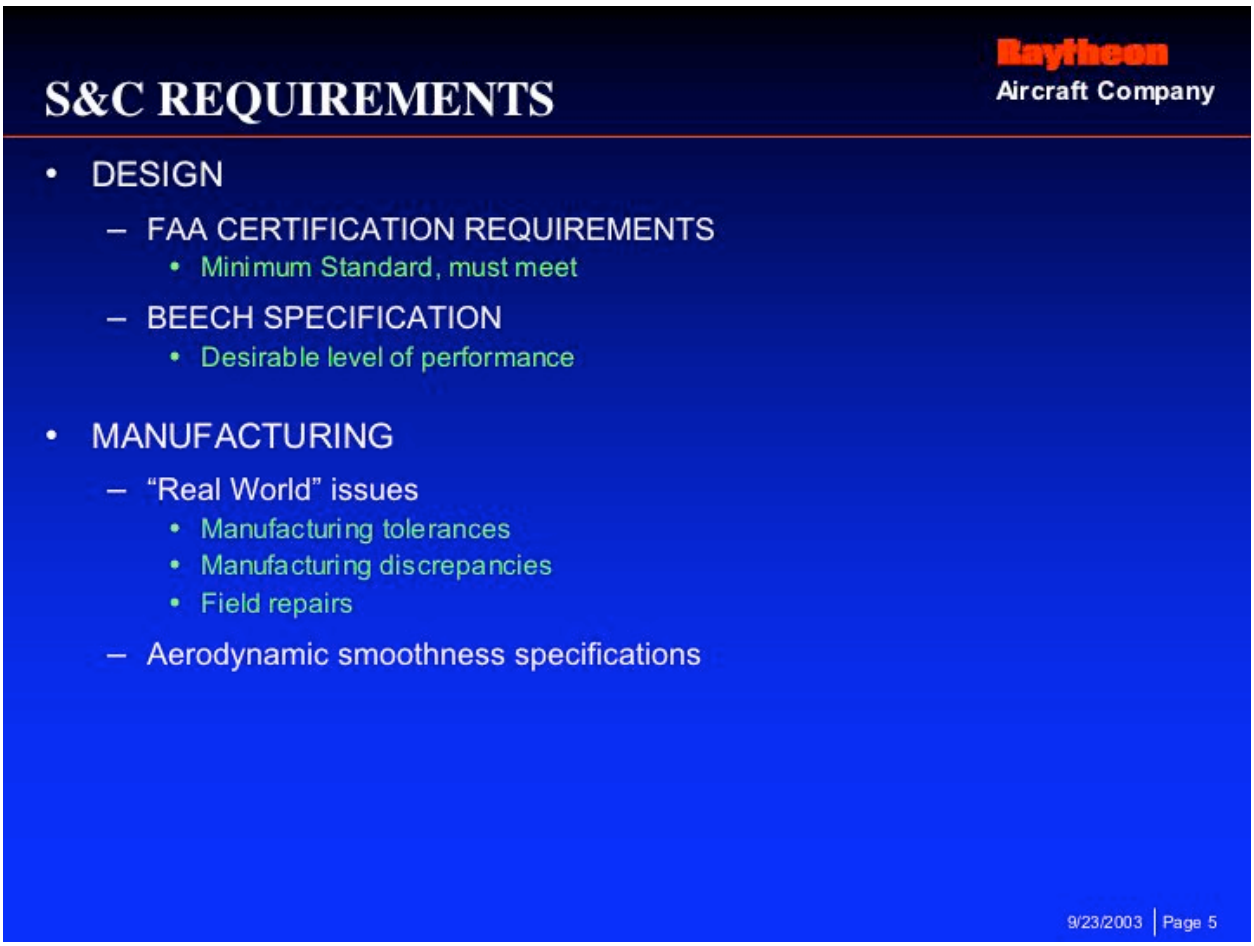
At the bottom end there are the piston-powered Bonanza and Baron. They are followed by the King Air products; C90A, 200, & 350 with 4, 6, & 8-passenger cabins respectively.

In the jet market, the base product is the Beech Premier 1 followed by the Hawker 400XP (previously the Beechjet), the Hawker 800XP, and finally the Hawker Horizon which is in flight test now.



Beech and Hawker also have a long tradition of producing special-mission aircraft. A few examples are shown here.

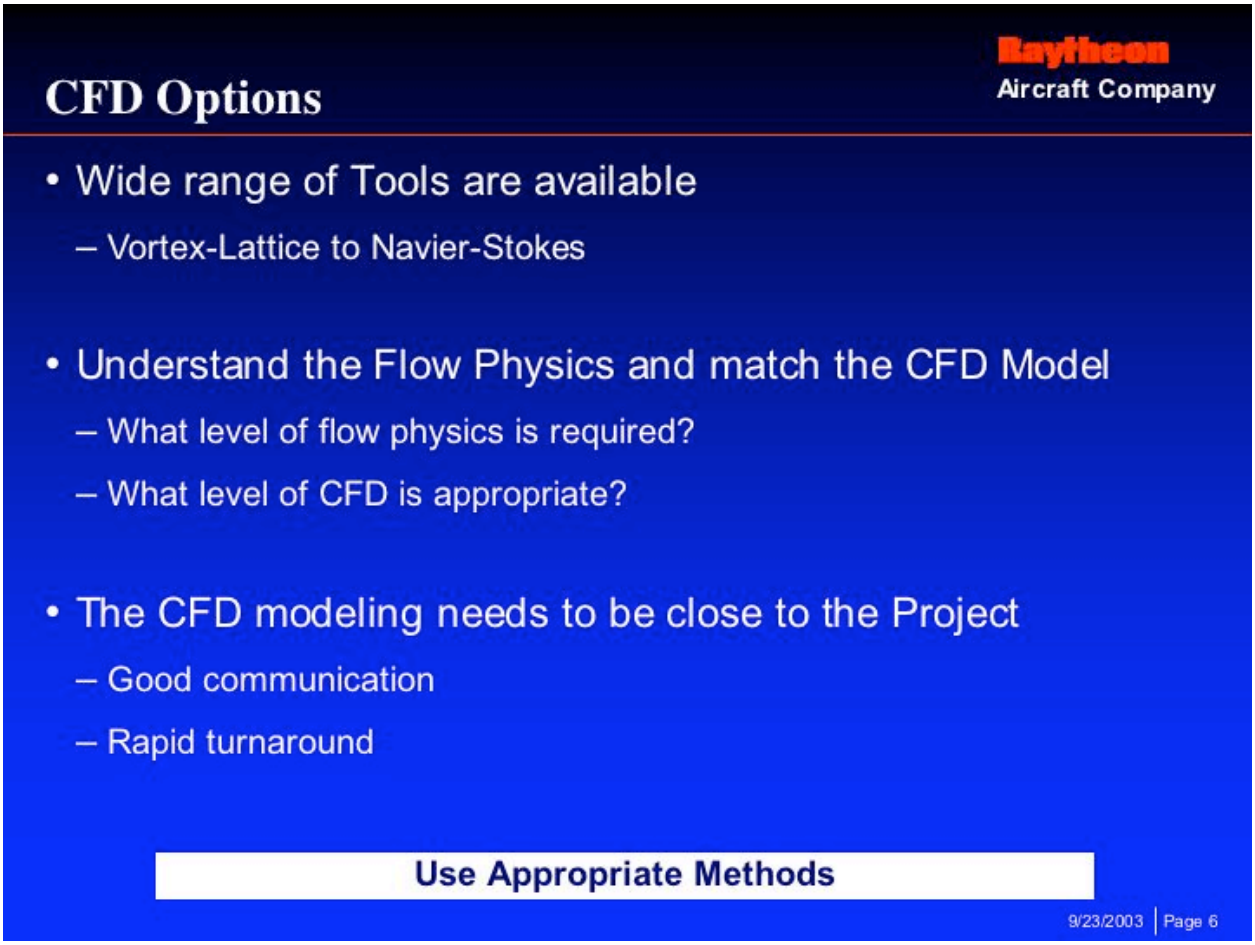
The S&C engineer needs tools to rapidly and accurately address the technical issues in all phases of the airplane design and production. Some of the requirements are hard and fast such as those found in the certification regulations. Other issues demand the use of engineering judgment, often without adequate data for making the decisions. That is where CFD can provide the needed information and insight into the physics of the flow situation.



There is a wide range of CFD tools available to an aerodynamicist. The aerodynamics engineer should be familiar with the features and limitations of each of these tools in order to make the best decision of how to proceed.

Understanding the flow physics of a configuration is of paramount importance in solving the problems on a project. Is it an inviscid problem? Is it a viscous problem? What level of CFD analysis is appropriate to generate the needed answer?

Ideally, the CFD modeling needs to be done by a member of the project team so that there is good communication. In addition, it is important that the CFD analysis be timely. The time to respond can easily make or break the usefulness of CFD to the project.

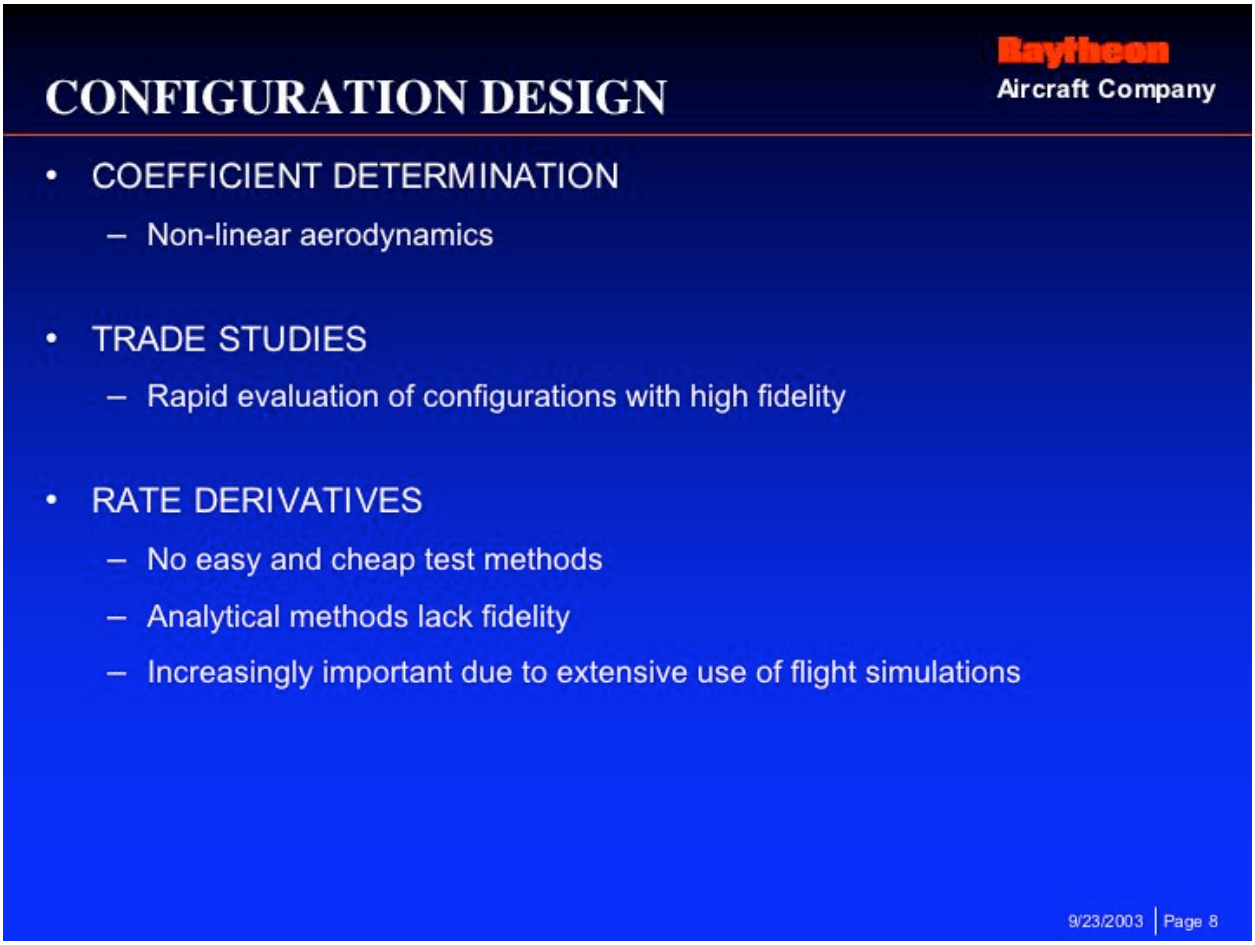


What are the generic areas of interest that repeatedly appear in the various projects?

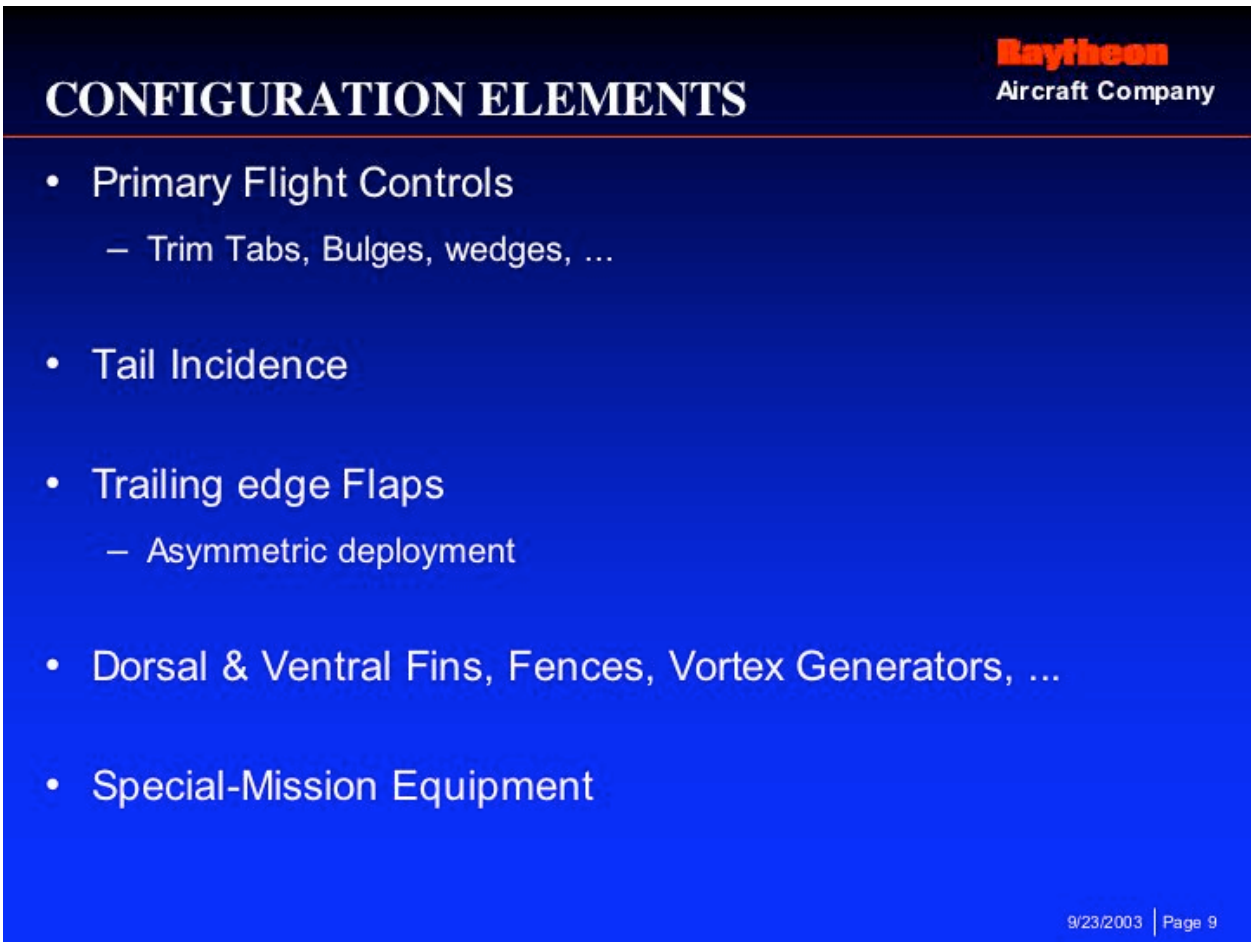
Empirical methods and closed form solutions are useful for linear coefficients, but the interesting problems often involve non-linear coefficients.

It is too costly to evaluate a range of configurations in the wind tunnel during development. Using CAD and modern gridding software, it is possible to evaluate many configuration changes for a wide range of flight conditions by using multiple CFD codes before the loft lines for the first wind-tunnel model are set.

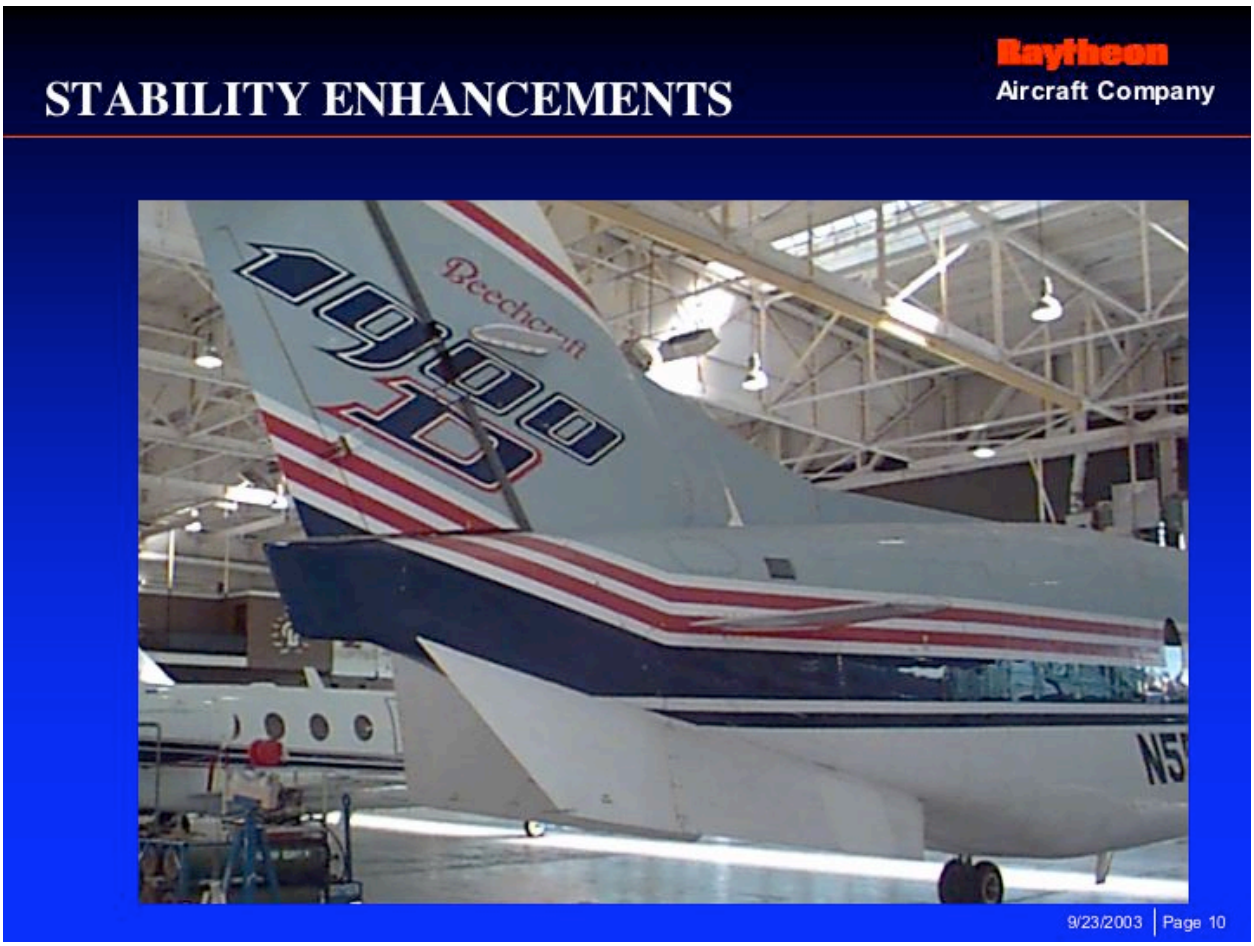
Rate, or rotary, derivatives are also difficult to estimate and even harder to measure in a wind tunnel. Accurate rate derivatives are needed for the simulations which are becoming more and more a part of the S&C toolbox.



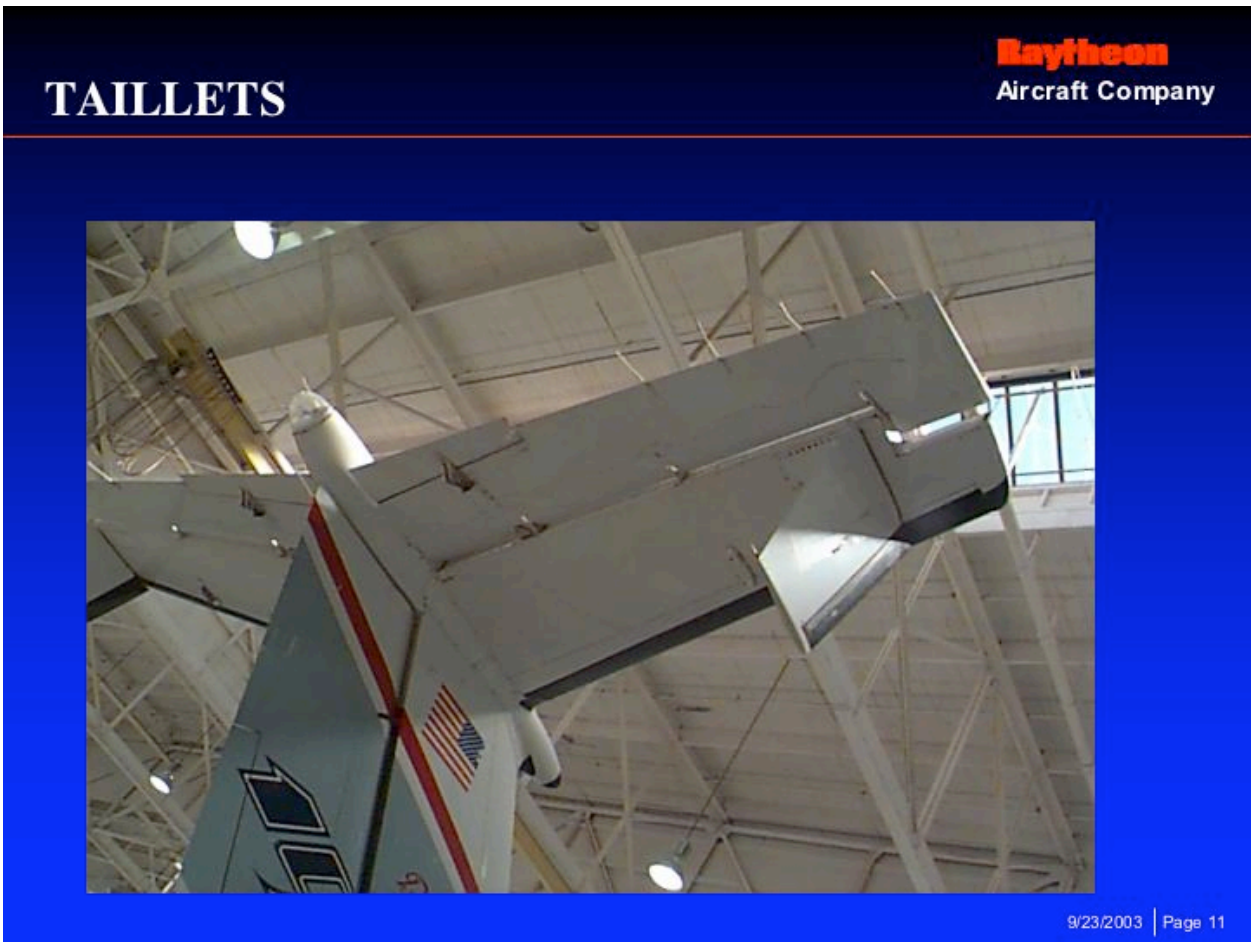
There are many different elements that can influence the handling qualities and performance of an airplane once the basic configuration has been defined. It would be useful to have proven CFD techniques to investigate these elements and help with their design and implementation.



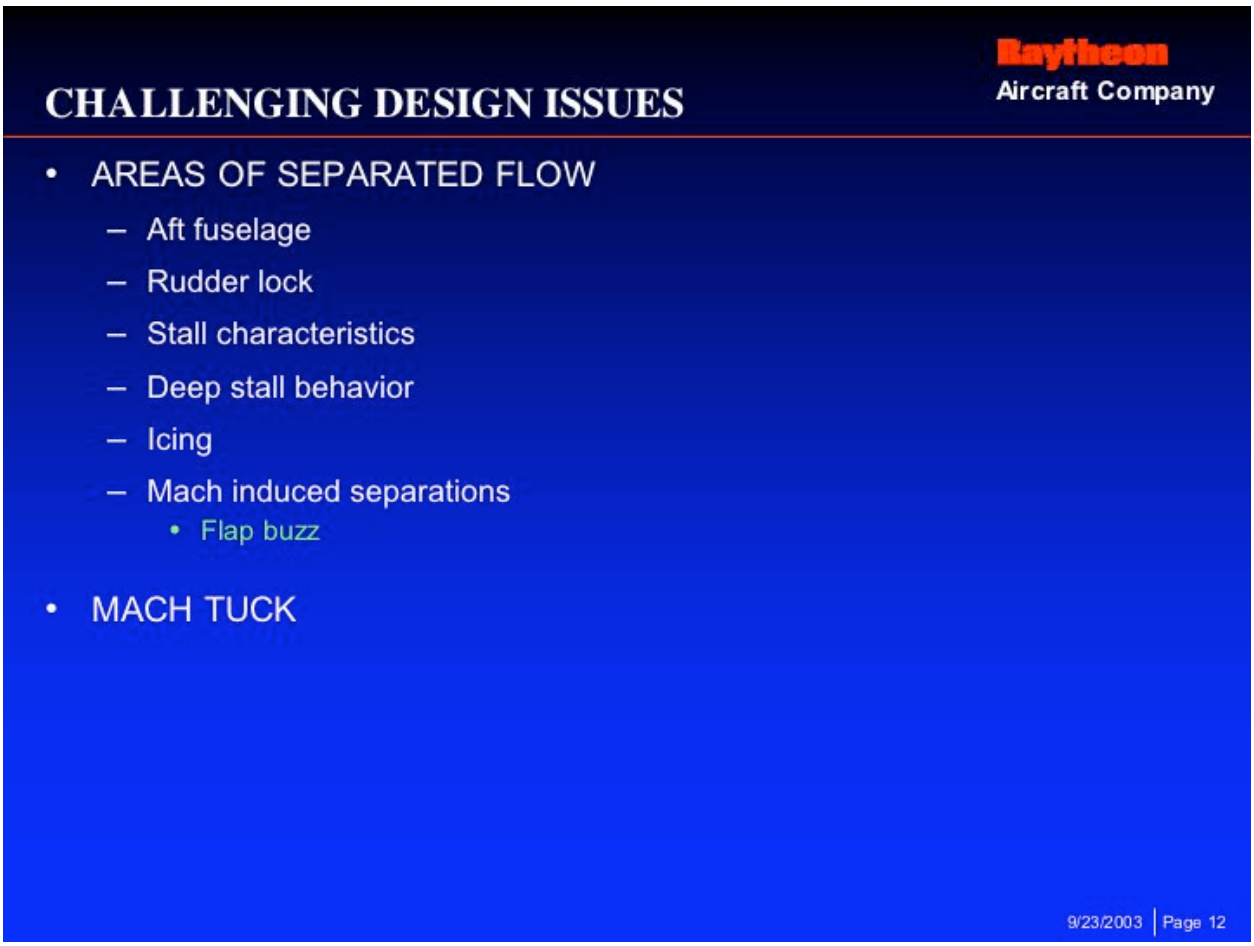
A completely new tail isn't always the best answer for the financial success of the project. Sometimes adding a few devices will do the trick.



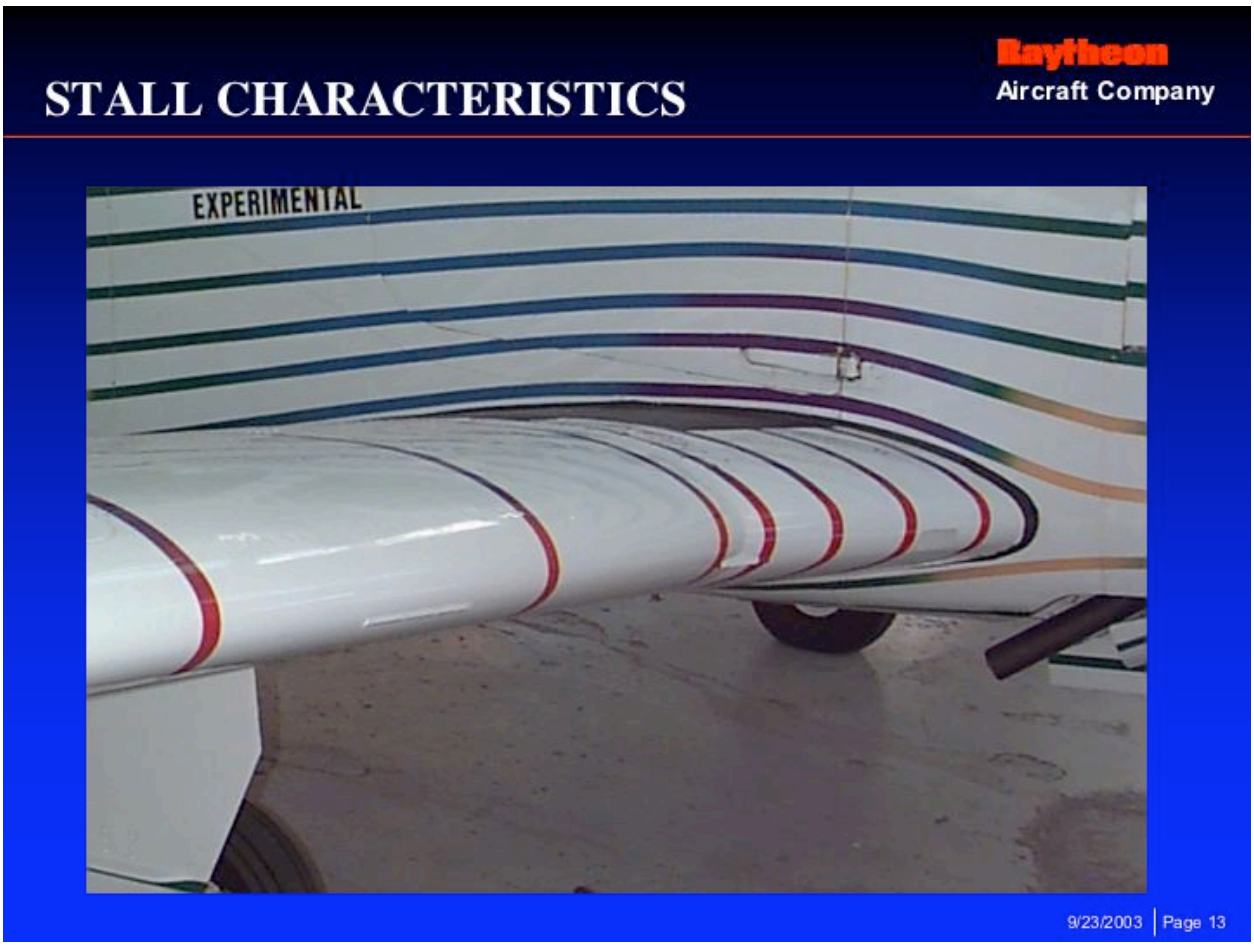
A larger vertical tail adds weight. Small appendages can provide the extra area. These taillets actually reduce some of the critical loads.



Separated flows due to high adverse pressure gradients are hard to analyze and lead to many undesirable flight characteristics. Mach induced separations can lead to control surface or flap buzz. The effects of ice accretions are becoming increasingly importance as regulations are tightening up. Highly swept wings are becoming more common and require extra care in the design.



Subtle leading edge strips are used to control the stall (and yes those are VSAERO-generated streamlines with the local pressure distribution superimposed by the changing color of the stripes).



This useful pre-flight cup holder also provides very tame stall characteristics and excellent spin prevention and recovery. The design method was “cut and try”.

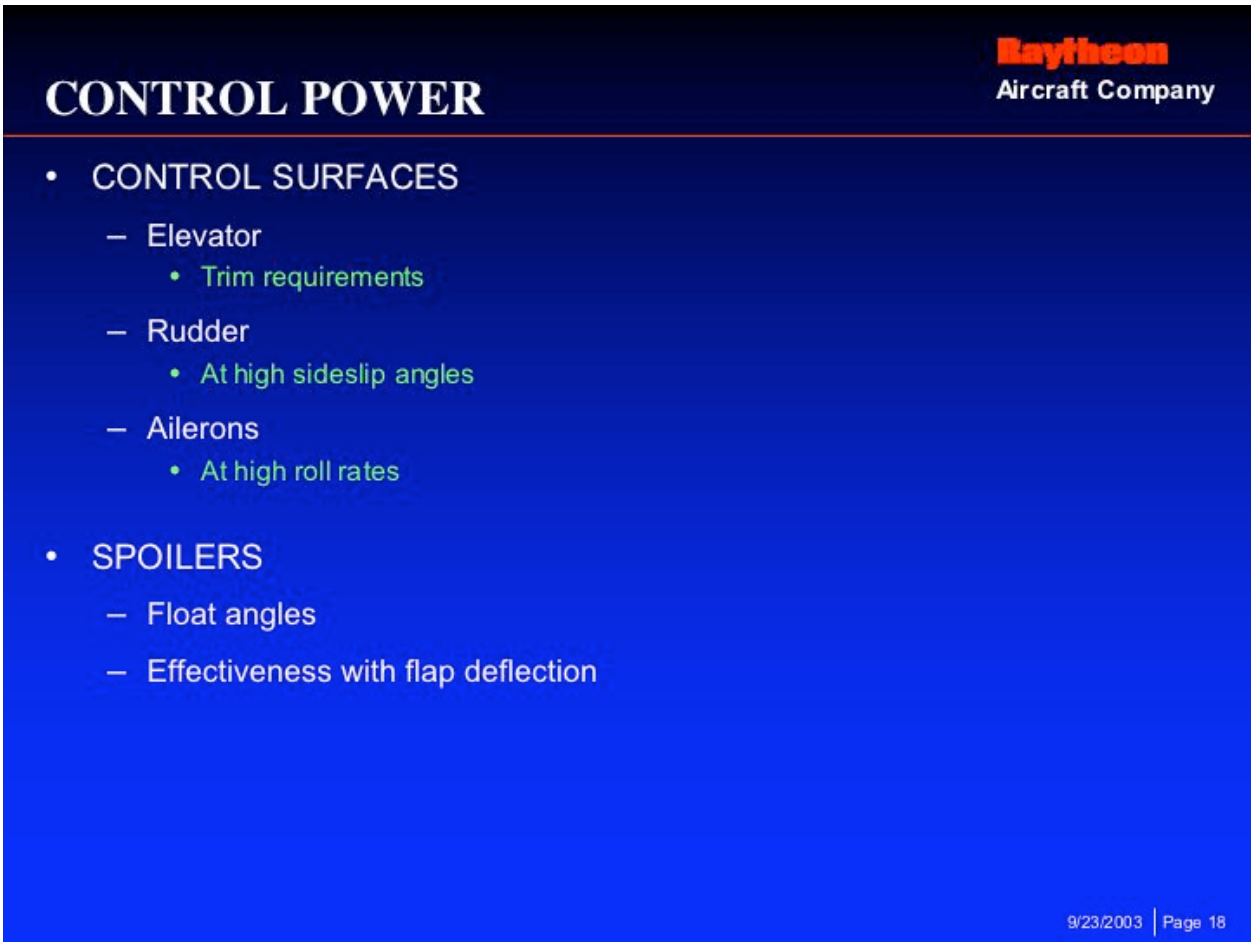
Vortilons are powerful flow control devices. They are normally added during developmental flight testing.

No, that's not a manufacturing glitch. This small leading-edge discontinuity is intentional and generates a lower stall speed. Not all vortex devices are big and ugly. (If anything, maybe it should have been slightly bigger so that there would have been fewer comments about how manufacturing must have goofed up.)

These VG's were used to eliminate an uncommanded, high-altitude, long-period, pitch oscillation. Probably could do it with fewer, but that would have required more testing.

Would an NS calculation now allow us to check for this before flight?

Control systems are no longer limited to a single surface. Using spoilers in conjunction with ailerons is common and almost necessary given the current certification regulations. Multiple spoiler panels are used for safety and can also double as speed brakes. Spoiler effectiveness with flaps deflection in always an interesting study where CFD methods are heavily relied upon.



Predicting control surface hinge moments is very difficult. Wind tunnel tests can sometimes lead to incorrect conclusions due to limitations of Reynolds number and instrumentation sensitivity. Re-design is sometimes required late in the program. Accurate CFD tools could be very valuable.

HINGE MOMENTS

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- Manual or Boosted Controls
  - Accurate hinge moment information required for decision
- Aerodynamic Balance
  - In all flight conditions
- Pilot Effort
- Rudder Lock
  - Over boosted controls at high sideslip, engine out
- Float Angles
  - Control system failures
- Manufacturing tolerances

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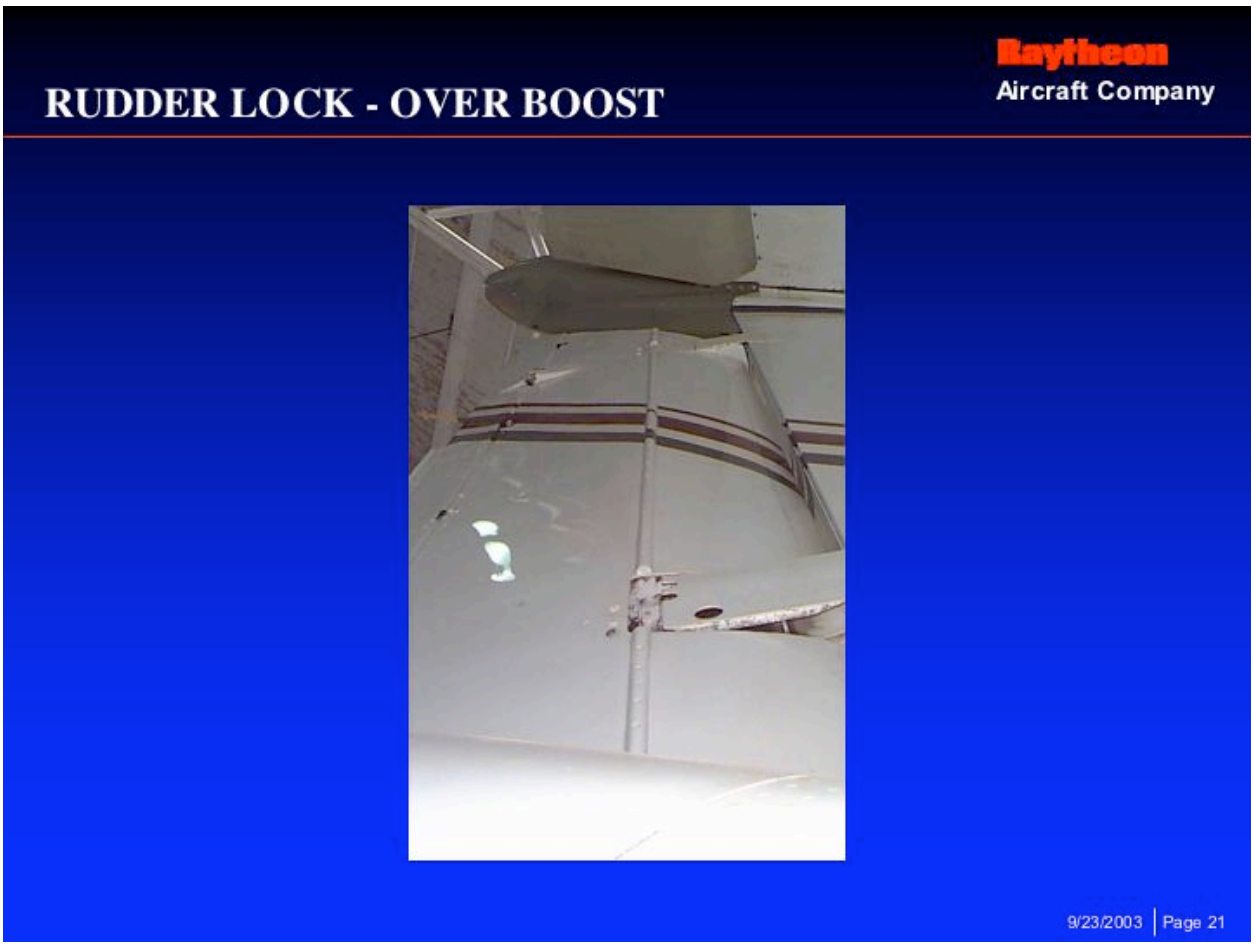
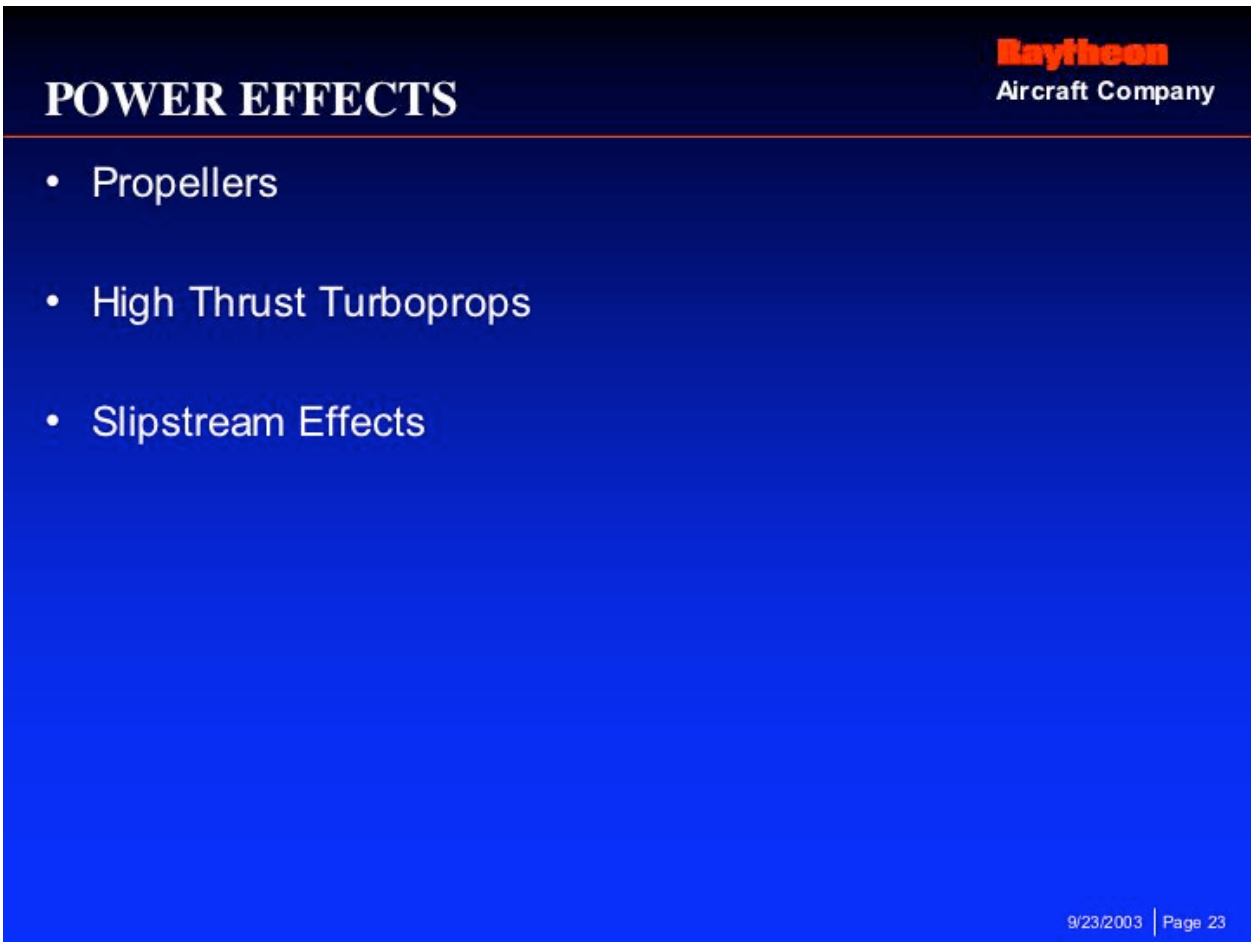
This is a very small wedge in front of an aileron, but has a very large effect on the hinge moment. Sometimes it just doesn't take much.

Rudder lock can sometimes be remedied by employing flow tripping devices. This stall bar on the rudder "sucks" the rudder back from a possible over boosted condition.

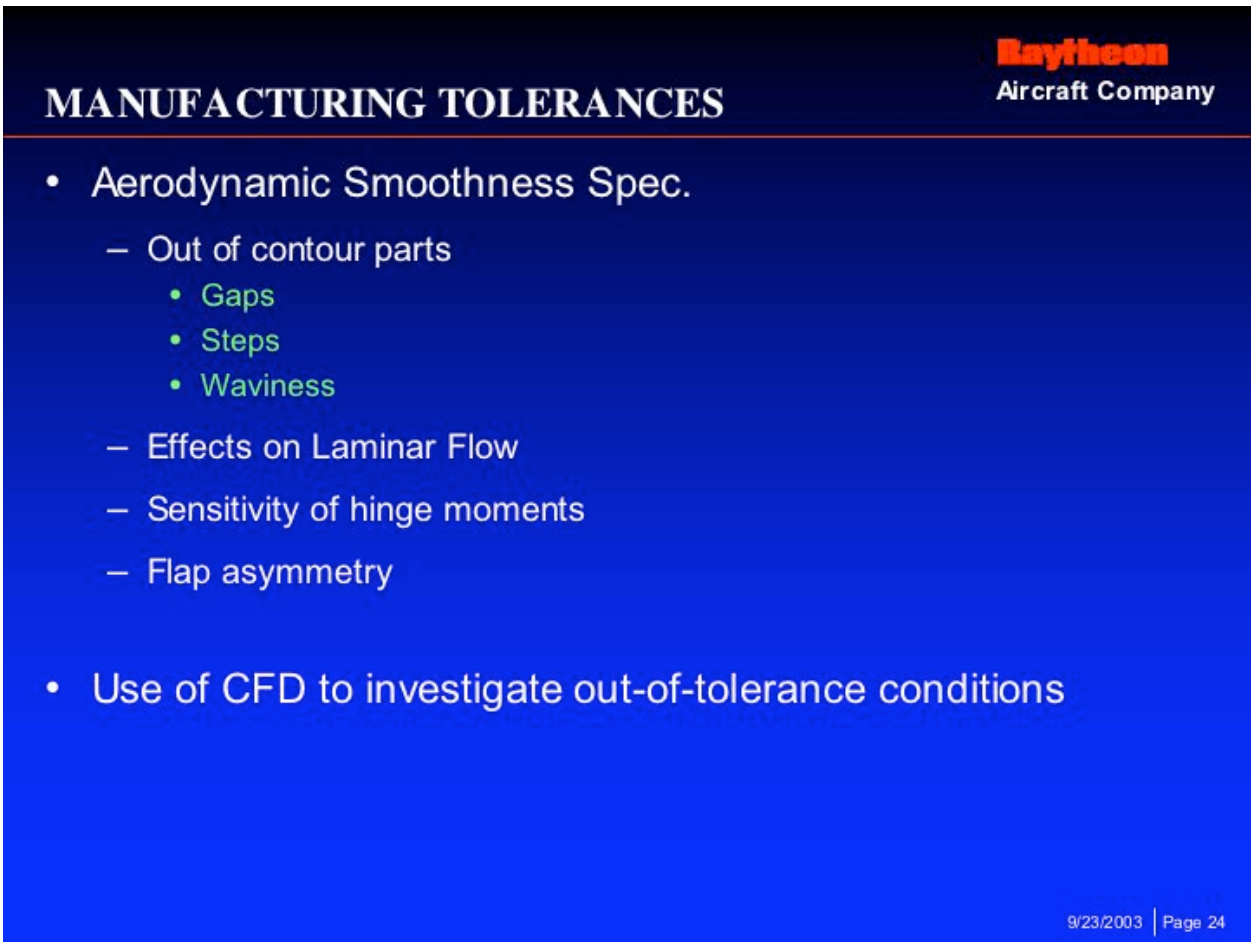


In meeting the minimum control speed in a multi-engine airplane, the rudder must provide large control forces for relatively small pilot effort. A bulge on the trailing edge can help balance the control force as a function of sideslip angle as opposed to that due to surface deflection. This provides freedom from rudder lock while keeping pedal forces low for the engine out condition.

Turboprop airplanes require consideration of slipstream effects. They are often also capable of very high angles of attack due to the ability of the airplane to "hang on the prop" at high power settings and low airspeeds. While powered wind-tunnel tests are common for these aircraft, the dynamic pressure and Reynolds number for these tests are very low. The use of validated CFD methods for these flight conditions would be of great benefit.



Manufacturing always struggles to build airplanes exactly the way we design them. Tolerances are exceeded, parts are dropped and damaged, and repairs are made. The aerodynamicist must decide whether to approve or disapprove these out-of-tolerance conditions. Usually there is little or no data to support the engineering decision. CFD could help.



There are other disciplines on the project team that also depend on S&C results.

Simulations are used during development, but also used through the life of the product for training.

Loads are calculated for a conditions throughout the entire operating envelope of the aircraft. In order to accurately trim the plane or fly a specific maneuver, the S&C coefficients need to accurate. Some loads may be pilot-effort limited. Without good hinge moment estimates, extra conservatism will needed to insure a safe design.

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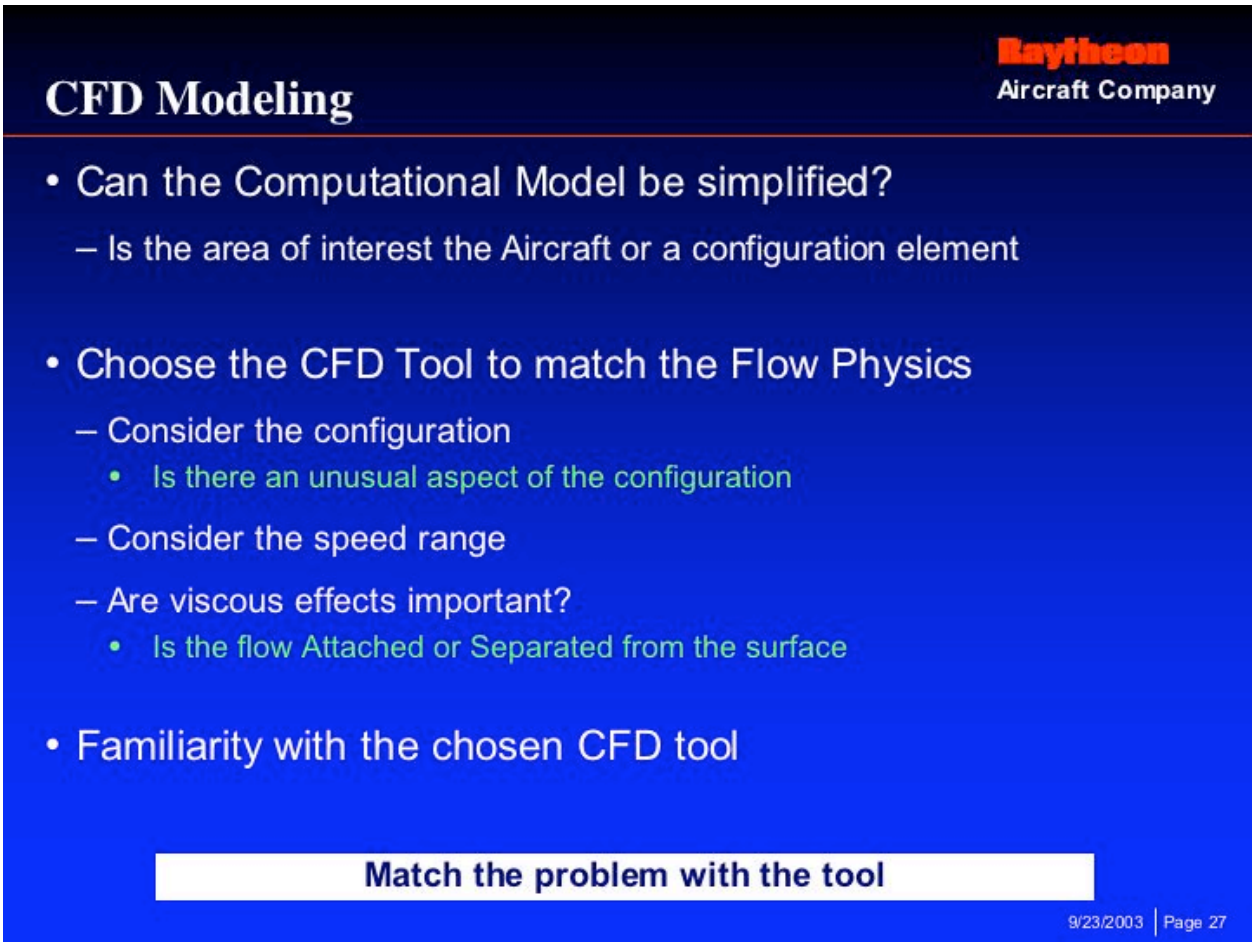
CFD Modeling for S&C Analysis

Here are some basic considerations to develop a CFD model.

Can the model be simplified? Do I have to model the entire aircraft or will a smaller model suffice? In fact, how small can I make it in order to answer the question reliably and quickly?

Match the physics of the problem with the CFD tool to be used:
- Is there a feature of the configuration that will require special care or a special technique to model? What level of CFD is required.
- I may still need transonic capability to obtain accurate leading-edge suction at stall.

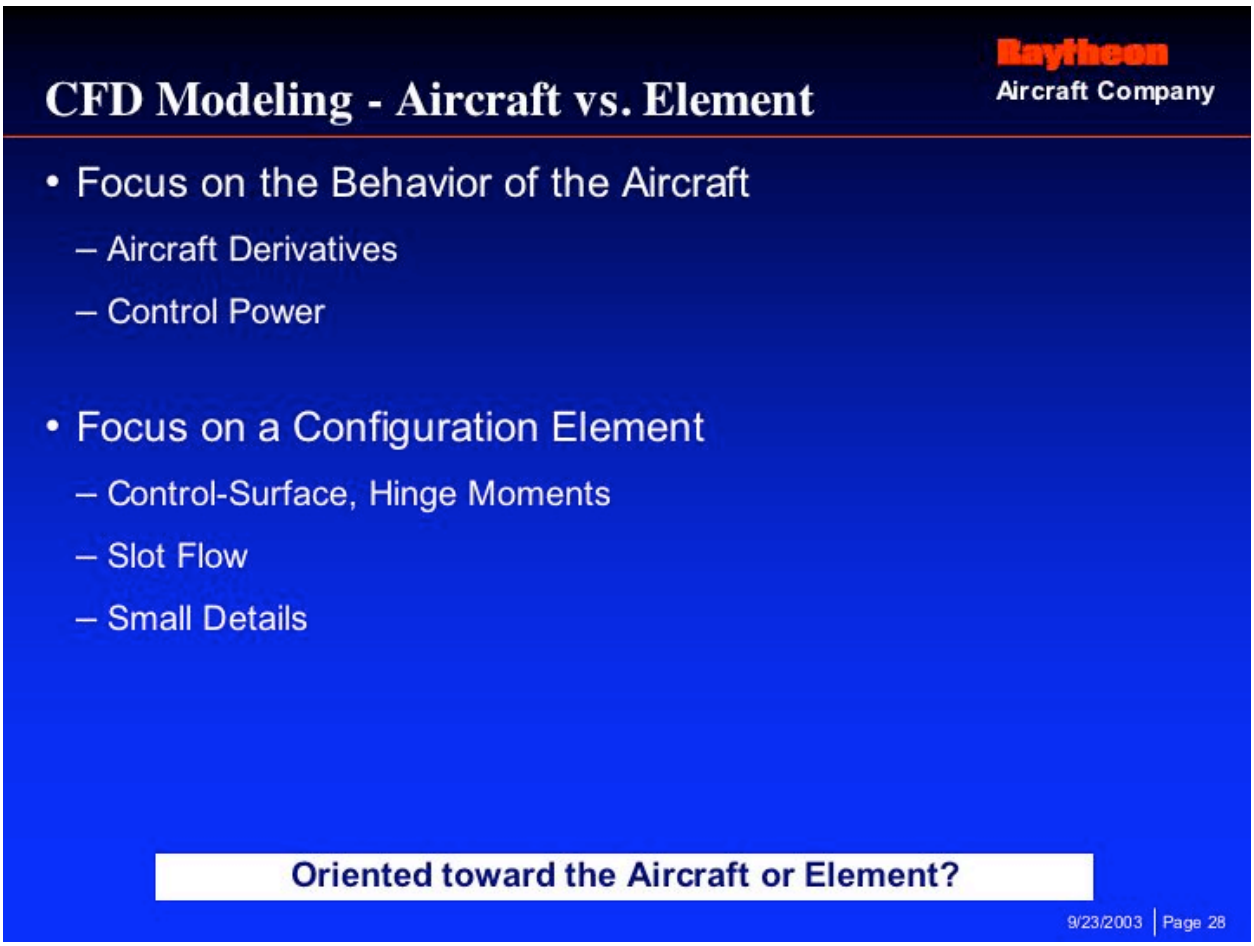


- Is the flow attached or separated? If separated, is it from the trailing edge or is it a leading-edge vortex? The CFD engineer should use this to help select the method of analysis.

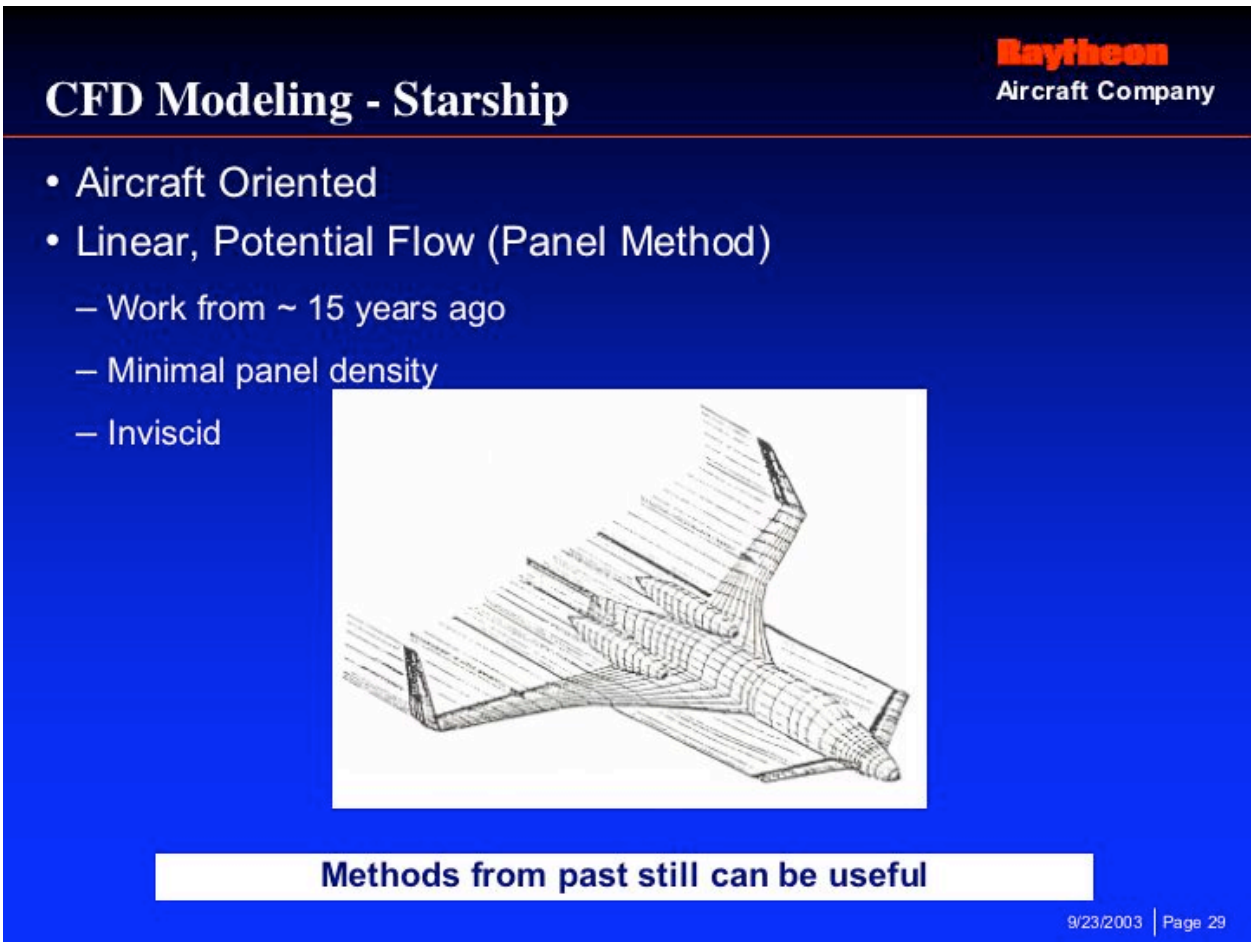
Unless the engineer is familiar with the CFD tool, the result will be neither quick nor calibrated.

When the problem focuses on the Aircraft, we are interested in gross effects.

When the problem is at the configuration element level, we need to have the appropriate detail in our CFD models.



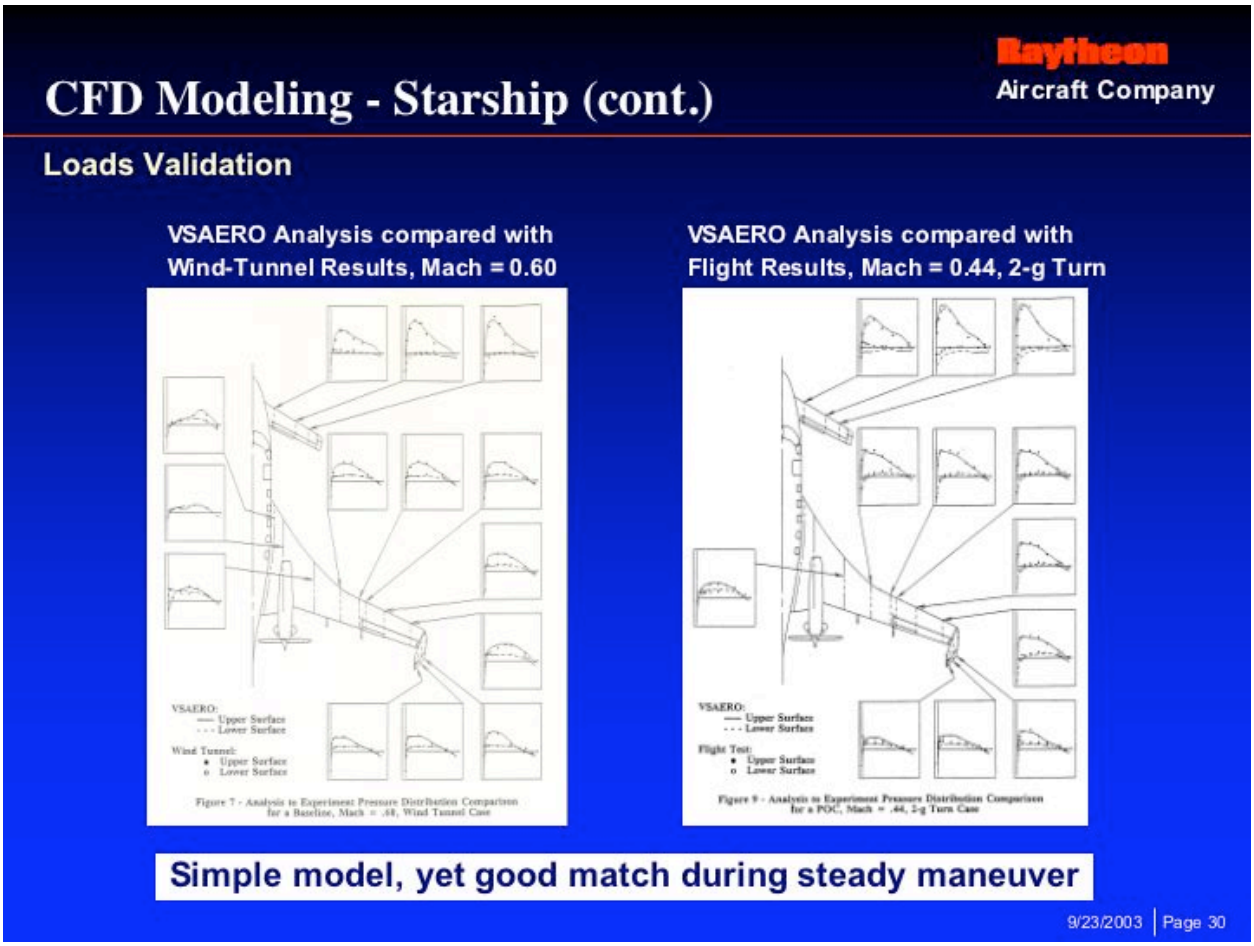
Here is an example of an Aircraft-Focused modeling from many years ago. This type of modeling is still appropriate for many cases and is used regularly in loads analysis. Although the results on the next page are inviscid, it is also easy to add viscosity to these models now.



These plots were used to show the correlation of analysis with experiment for the aircraft loads.

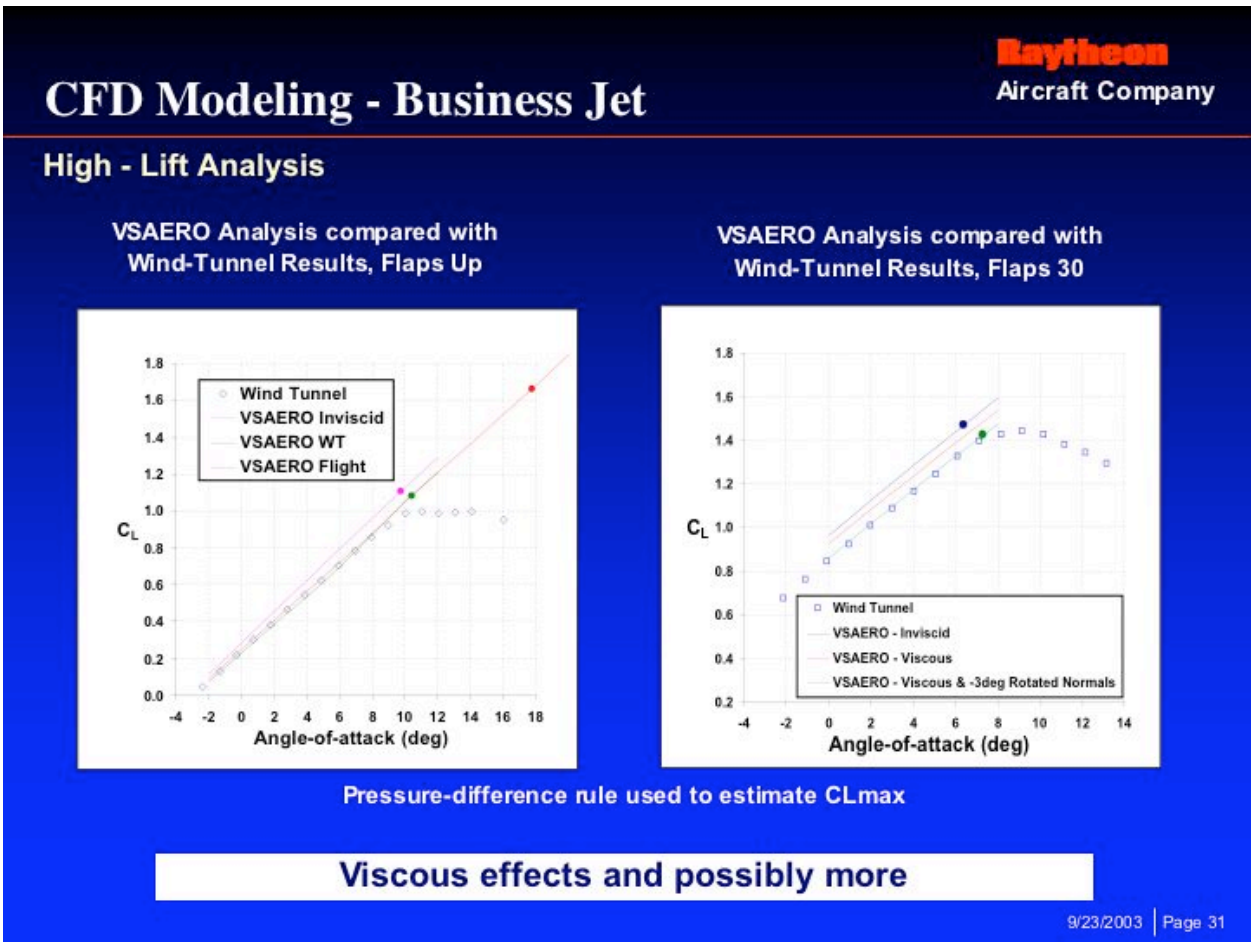
This simple model provided an excellent match to the tightly-controlled, wind-tunnel model and good agreement to the 85% Proof-of-Concept (POC) Demonstrator during a steady 2-g turn.

(See Applied Computational Aerodynamics, Ed. Press Henne, Progress in Astronautics and Aeronautics, Volume 125 Published by AIAA, 1990, Chapter 16)

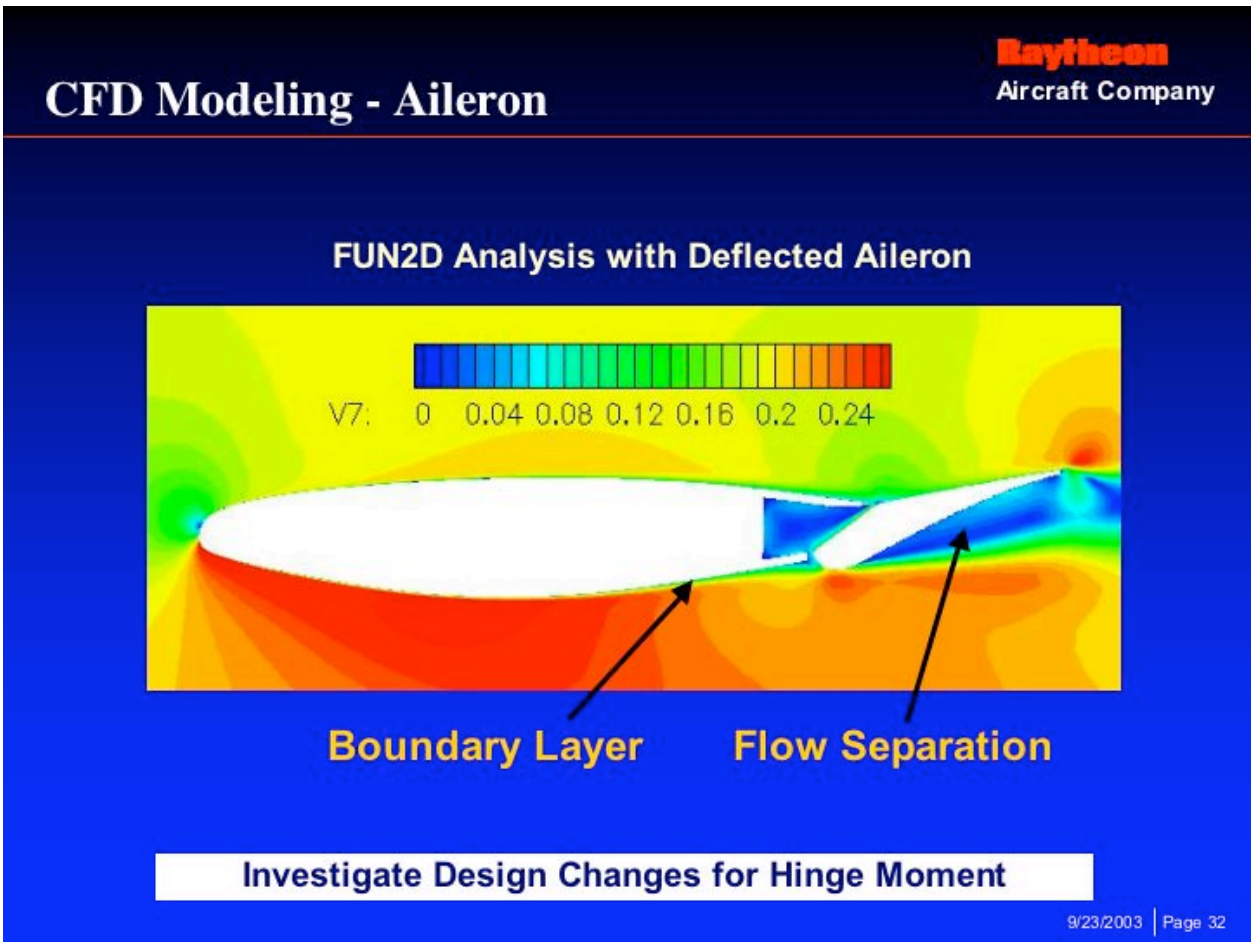


Typical lift and pitching moment behavior are shown here for a business-jet configuration. The solid circles denote estimated Clmax levels using the trailing-edge, pressure-difference rule.

Note that for the flaps 30 case, the experimental data matches an effective flap deflection that is 3 degrees less than the geometric angle for the model as designed. This tends to indicate that the bracket tolerance and aeroelastics of the flap installation combine to reduce the effective flap deflection.

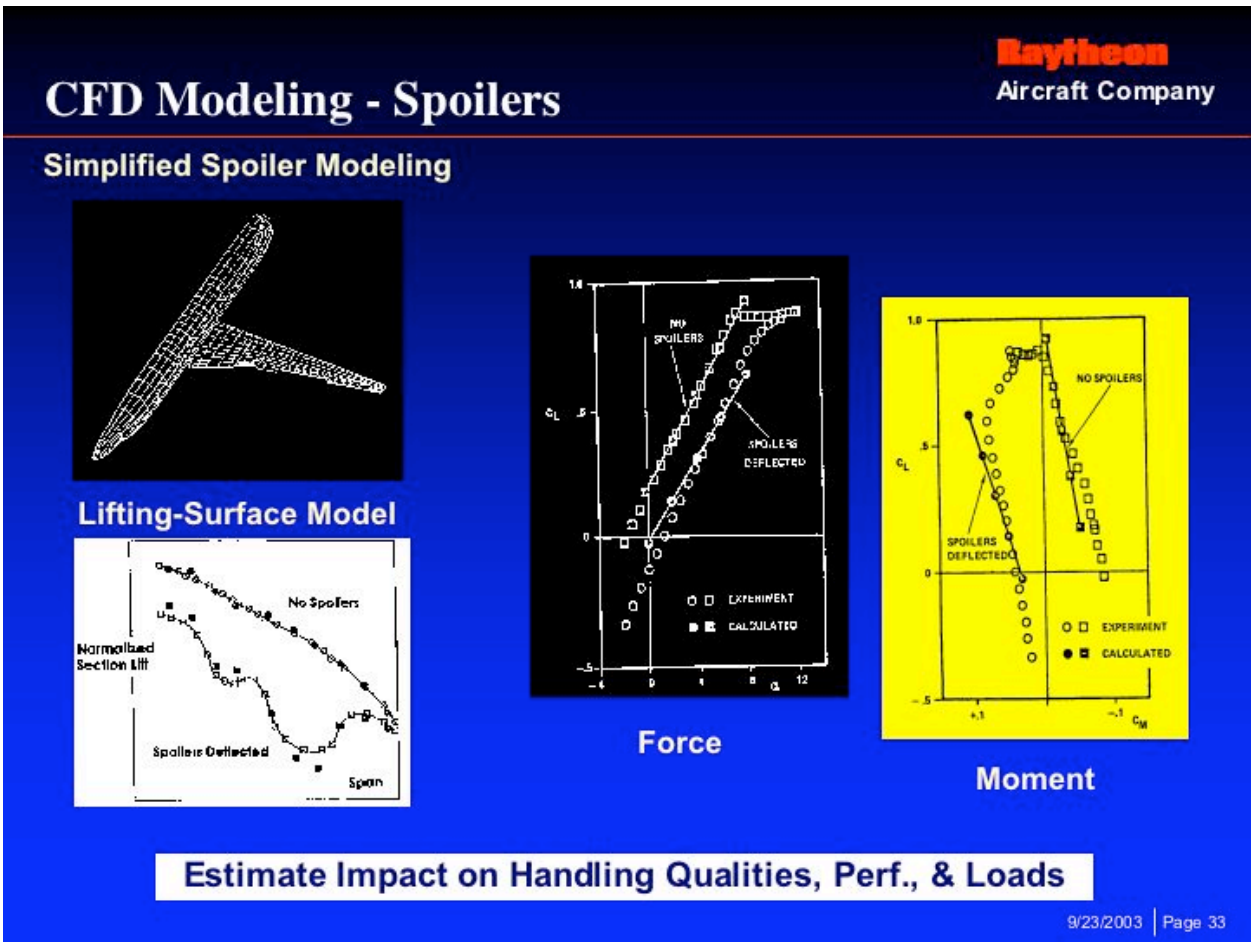


Medium and small-size business aircraft typically have unpowered control surfaces. This example shows how CFD codes can be used to study the complex interactions of various aileron shapes with the wing and cove. These results can be used to evaluate these shapes and choose ones for further evaluation in a wind tunnel or in flight.

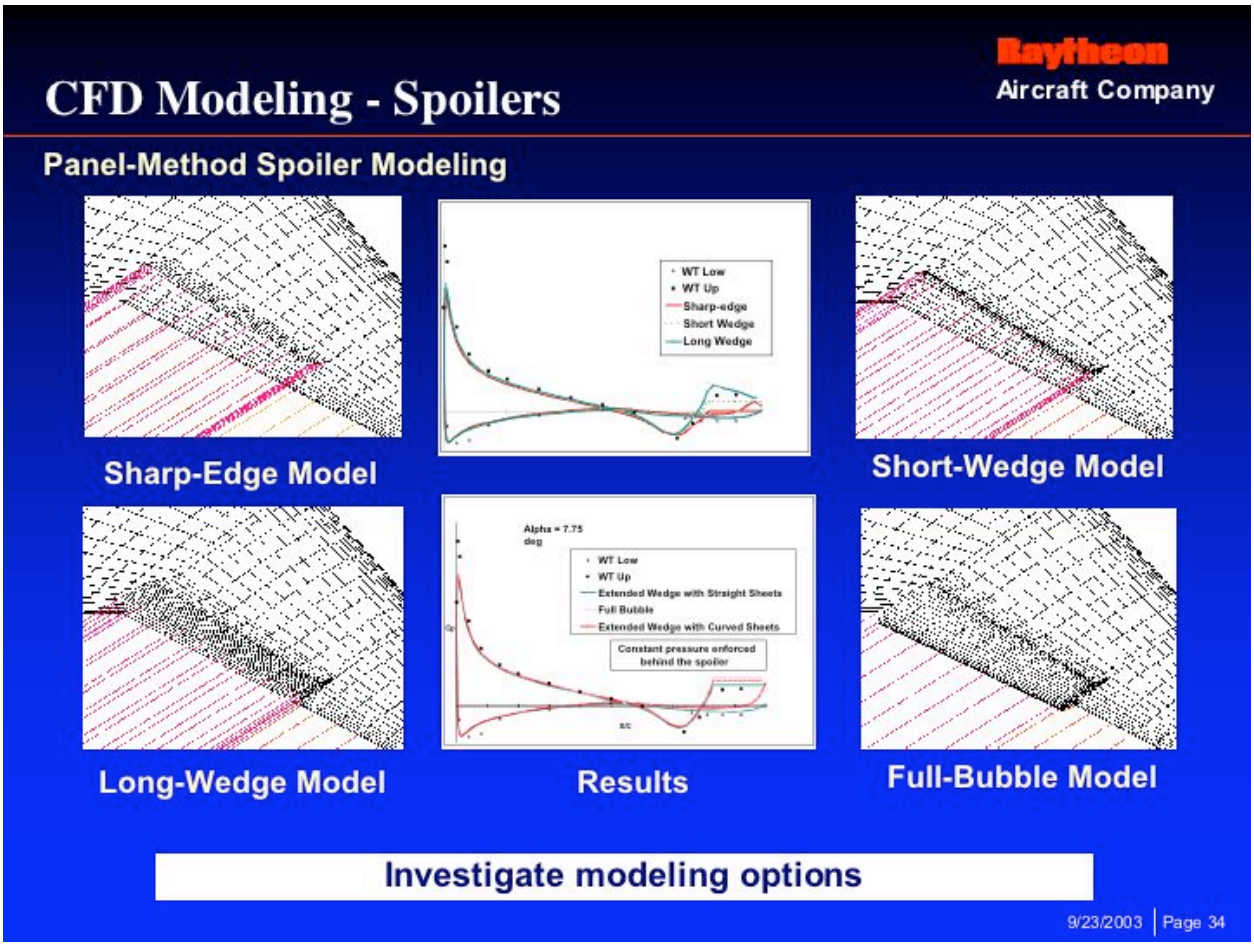


This is an example from over 20 years ago that shows even simple-lifting surface methods have their place in the preliminary assessment of a configuration.

This simple modeling accurately matched the spanload and force and moment curves in the linear regions.

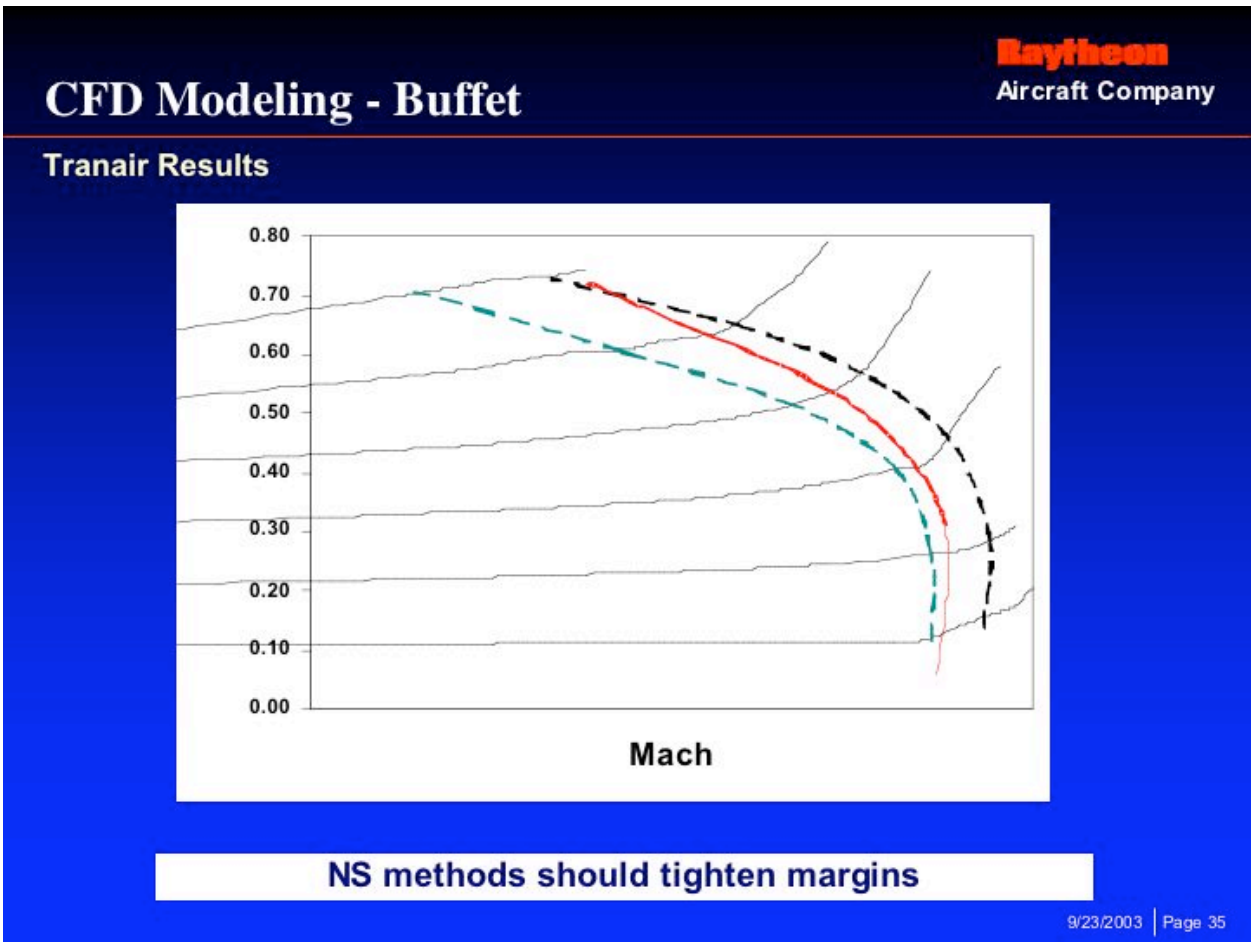


More recently (see AIAA paper # 98-2739) panel method geometries have been used to effectively simulate deflected spoilers with VSAERO and Tranair.



The buffet boundary for a business jet is an important limit to understand. This plot shows how the boundary-layer behavior from Tranair results can be used to make a useful estimate of this limit (see AIAA paper # 2000-0380).

The use of Navier-Stokes codes now could possibly make the estimate even better.



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Conclusions

It is important for an aircraft program to be able to accurately estimate the behavior of the entire aircraft and also model details of the flow past specific configuration elements. There will likely need to be more than one CFD model to efficiently get the needed results.

A CFD plan for a program should utilize appropriate tools for each phase.

POTENTIAL IMPACT OF CFD ON S&C

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- Basic program requirements
  - Ability to estimate overall aircraft behavior
  - Ability to model flow details
- Consider appropriate CFD methods for all program phases
  - Concept development
    - Rapid design iteration
    - Evaluation of unusual design features
  - Advanced design
    - Rapid development of total body coefficients for simulations
  - Production design
  - Testing and certification
    - Provide understanding of unexpected results
  - Continuing support
    - Evaluation of manufacturing discrepancies
    - Understanding of the effects of field repairs on airplane flight characteristics

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A Greybeard's View of the State of Aerodynamic Prediction

NASA COMSAC Symposium

Hampton, Virginia

23 September 2003

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Wind Tunnels

- Over 100 years of producing the data from which an extension variety of aircraft configurations have been built <u>and</u> successfully flown
- Even after 100 years, however, wind tunnels have limitations in the accuracy and types of data they can give us
- Nonetheless, we understand their strengths and weaknesses, and are able to handle them accordingly.

  - we have learned how to correct for sting and distortion, wall effects, blockage, etc

  - we have made allowances for less than flight Reynolds number

  - we have developed the art of tripping the boundary layer from laminar to turbulent
- In short, we have learned how to design and develop successful aircraft, even though they don't always perform up to our predictions.
- The primary problems with wind tunnels in the U.S. are:

  - most were built between 1930 and 1960

  - upgrades and upkeep are hard to come by

  - test techniques, data corrections, and productivity are lagging the more modern European tunnels

Wind Tunnels

- Over 100 years of successful aircraft, but
- Still limits in accuracy and types of data
- However, strength and weaknesses understood
  - sting and distortion
  - wall effects and blockage
  - Reynolds number and boundary layer

Wind Tunnels

- We can design and develop successful aircraft
- Primary problems in U.S.
  - most built in 30s to 60s
  - upgrades and upkeep difficult
  - techniques, corrections, and productivity lagging

Computational Fluid Dynamics

- With the advent over the past twenty years of very high speed computers with very large data storage capability, we can now solve the basic equations of fluid flow over a body with ever finer and complex grid systems
- The result, in my opinion, has been a mixed blessing:

  - we now have a very powerful tool in our effort to define and understand 3 dimensional transonic flow which has evaded us since the relativematuration of our understanding of 2 dimensional transonic flow achieved by the mid 1960s.

  - this evasion appears to be that we as a nation significantly reduced our aerodynamic research efforts. Whether this was caused by the cost of the race to the moon, the Vietnam War, or it was just too hard, I don't know. In any event our efforts toward understanding 3 dimensional transonic flow came to a virtual halt.

  - However, since at least the early 1990's, these seems to be a belief at the upper levels of NASA and DOD, that wind tunnels are too expensive and that, since we can now calculate the flows, we should shut down as many wind tunnels as possible and rely heavily on CFD.

  - as a result, there seems to be a steady procession of studies, panels, and assessments apparently looking for one which will conclude, in the extreme, that all he tunnels can go, and CFD will take over

  - I know this sounds paranoid, but I have been closely involved with enough of these studies to justify my paranoia.

Computational Fluid Dynamics

- Come to the fore as higher computer speeds and greater memory became available
- Made detailed flow calculation possible
- A mixed blessing

  - powerful tool to help understand 3D transonic flow

Computational Fluid Dynamics

- apparent belief in upper levels of NASA and DOD
  - wind tunnels too expensive
  - CFD can replace
- steady procession of studies
- paranoia ?

Synergy

- Wind Tunnels and CFD are not an either/or proposition.
- They are, in fact, highly complimentary tools that if used properly provide a synergistic effect to enhance our definition and understanding of the configuration.
- The strength of the wind tunnel is its ability to provide large amounts of data in a timely fashion. Literally millions of data points covering the ranges and combinations of speed, angles, deflections, and loadings can be obtained.
- The strength of CFD is its ability to investigate limited configurations and small ranges of variables without new wind tunnel models or parts, and providing a better picture of the total flow.
- At this time CFD has two areas of considerable usefullness:

  1. To narrow the range of basic configurations up front in the design phase, which limits the amount of preliminary design wind tunnel test configurations

  2. When a problem is encountered in the wind tunnel or later in flight test, CFD can be used the investigate the cause and possible fixes because the area for study is narrow in scope, not the full envelope.
- CFD is, however, dependent upon validation with wind tunnel data for problem investigation. Matches with oil flows, Pressure Sensitive Paint, pressure measurement, and standard force data must be achieved.
- Unfortunately, achieving a proper match can be time consuming while the proper grid size and distribution, the best turbulance model, etc are found.
- It would greatly benefit any new aircraft development or significant modification program to develop CFD definitions in areas where problems are most likely to arise in flight. This will reduce or eliminate the time required to achieve validation in the area of investigation.

Synergy

- Wind tunnels and CFD are not an either/or proposition
- Highly complimentary tools if used properly
- Wind tunnel strength
  - provide large amount of data
  - timely for program

Synergy

- ranges and combinations of
  speed
  angles
  deflections
  loadings

Synergy

- Strength of CFD
  - ability to investigate limited configuration and small number of variables
  - no models or parts, and a better view of flow
- CFD has two areas of considerable usefulness:
  - to narrow the number of configurations

Synergy

for wind tunnel testing during preliminary design

- to investigate to problems in specific areas

- CFD is, however, dependent upon validation when investigating specific aircraft problems
  - oil flows of prime importance

Synergy

- achieving a proper match can be time consuming
- new programs would greatly benefit from CFD definitions in likely problem areas before they arise

National Wind Tunnel Complex (NWTC)

- National Facilities Study Team established in early 1993.
- Representatives from NASA, Department of Commerce, Department of Defense, Department of Energy, Department of Transportation, and industry
- Aeronautics R&D Facilities Report issued in April 1994
  - most critical need is for new high Reynolds Number, high productivity subsonic and transonic wind tunnels
  - NWTC formed with offices in Cleveland
  - staff consisted of wind tunnel experts form both government and industry.
- Purpose of the NWTC was to supplement the existing NASA research-oriented tunnels by providing the aerospace industry with the ability to develop and design advanced, efficient aircraft.
- The emphasis was not just on aerodynamic capability, but also on high productivity and low operating cost.
- Initial plan were to build two tunnels:
  - subsonic tunnel with 20 million Reynolds Number capability in a 20X24 ft test section
  - transonic tunnel with 28 million Reynolds Number capability in an 11X15.5 ft test section.
- Later, the plan was consolidated into one tunnel whose primary capability was transonic, but could still be used for low speed, high lift tests. It would have a somewhat reduced Reynolds number capability at low speed, and a somewhat higher capability transonic using a 13X16 ft test section
- Eventually, the program was cancelled with three factors playing a primary role:
  - cost
  - financing arrangement
  - site selection

National Wind Tunnel Complex (NWTC)

- National Facilities Study Team - 1993
  - NASA
  - Departments of Commerce, Defense, Energy, and Transportation
  - Industry
- Aeronautics R&D Facilities Report - 1994
  - most critical need for two new tunnels

National Wind Tunnel Complex (NWTC)

- subsonic and transonic, each with high Reynolds number and high productivity
- NWTC office found in Cleveland
- wind tunnel experts from government and industry

• Initial plans

National Wind Tunnel Complex (NWTC)

- subsonic tunnel
  20 million Reynolds number
  20x24ft test section
- transonic tunnel
  28 million Reynolds number
  11x15.5ft test section

National Wind Tunnel Complex (NWTC)

- Later planning
  - consolidate into one tunnel

    13x16ft test section

    somewhat lower Reynolds number capability at low speed, and somewhat higher at transonic speed
- Purpose of NTWC

National Wind Tunnel Complex (NWTC)

- supplement NASA research oriented tunnels by providing industry with ability to develop and design advanced, efficient aircraft
- emphasized
  - aerodynamic capability
  - high productivity
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National Wind Tunnel Complex (NWTC)

- Cancelled with three factors playing primary role
  - cost
  - financing arrangement
  - site selection

Paul Rubbert Wright Brothers Lecture

- In 1994, Paul Rubbert, Boeing's Chief of Aerodynamics Research, gave the AIAA Wright Brothers lecture.
- He described the evolving role of CFD in the commercial aircraft design process with emphasis on timeliness and market share.
- While concentrating on CFD throughout the lecture, he states that wind tunnels are still vital.
- To summarize his comments:

  - CFD strength is to rapidly and cheaply carry out a very small number of simulations

  - these are concentrated on the design points

  - the rest of the flight envelope must also be accurately defined, requiring the coverage of the full range of speed, angles, and deflections.

  - these results must be available early for flight simulators, handling qualities investigation, and crew training.

  - the wind tunnel strength is to be able to generate the required data within acceptable limits of cost and flow time, a task that is unthinkable with CFD.
- A complete transport development involves approximately 2 1/2 million aerodynamics data points.

  - only a tiny fraction are CFD

  - <u>but</u>, this is an extremely strategic and effective fraction due to its concentration on the design points.

Paul Rubbert's Wright Brothers Lecture

- Paul Rubbert - Boeing Chief of Aerodynamics Research
- AIAA Wright Brothers Lecture - 1994

  - evolving role of CFD in commercial aircraft design process, timeliness, market share

  - wind tunnels still vital

Paul Rubbert's Wright Brothers Lecture

- Summary

  - CFD to rapidly and cheaply run a very small number of simulations

  - concentrated on the design points

  - use wind tunnel to define rest of the flight envelop speed, angles, deflections

Paul Rubbert's Wright Brothers Lecture

- These results needed early
  - flight simulators
  - handling qualities investigations
  - crew training
- Wind tunnel can generate large volume of required data within acceptable limits of cost and time

Paul Rubbert's Wright Brothers Lecture

- this task is unthinkable with CFD

- Complete transport development
  - 2 1/2 million aerodynamic data points
  - tiny fraction are CFD, but
  - these are extremely strategic and effective fraction
  - concentrate on design points

Recommended CFD Priority for S&C

- With the emphasis for the past twenty-five years on stealth and Relaxed Static Stability (RSS), the importance of accurately predicting Cm0 has become very important. Accurate predictions of Cm0 has been especially difficult in the wind tunnel. The consequences can be serious with short coupled configurations which rely on an up load on the horizontal for low approach speeds, flying wings (including deltas) where the controllers and high lift system are the same, and the need for low signature in the combat mode.
- In both of these configurations an error in Cm0 causes a change to horizontal trim deflection which may have a significant effect on approach speed and possibly be control limiting. Changes in trim in the combat mode may have an adverse effect on radar signature. I strongly recommend that a high priority be placed on an investigation to solve this problem with appropriate use of CFD.

Recommended CFD Priority for S&C

- Stealth and Relaxed Static Stability Aircraft
  - short coupled
  - flying wing and deltas
- Accurate prediction of Cm0 Is vital to these types of configuration
  - combat phase radar signature
  - low approach speed

Recommended CFD Priority for S&C

- Recommend a high priority investigation of CFD to help provide accurate prediction

Synergy of Wind Tunnel and CFD in the Abrupt Wing Stall Program (AWS)

- While not an aircraft development program, AWS was the result of the effort which solved the F/A-18E/F pre-production configuration wing drop problem. This program utilized both wind tunnel and CFD over approximately three years to develop a better understanding of what causes wing drop, as well as a number of techniques and figures of merit to identify the possibility of wing drop (or some kind of objectionable lateral activity) occurring while still in the design and pre flight development phases. These techniques include:

  - change to negative slope in the wing root bending moment and lift curves

  - use of spanwise loading and the rate of change of spanwise loading with angle attack

  - various types of lateral activity occurring during wind tunnel tests on the Free to Roll rig

  - measurement of steady and unsteady pressure distributions a appropriate chord locations

- While we still aren't there in having a full understanding of the various contributions to abrupt wing stall, this program was a major step in that direction.

Synergy of Wind Tunnel and CFD in the Abrupt Wing Stall Program (AWS)

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  - change to negative slope in the wing root bending moment and lift curves

  - use of spanwise loading and the rate of change of spanwise loading with angle attack

  - various types of lateral activity occurring during wind tunnel tests on the Free to Roll rig

  - measurement of steady and unsteady pressure distributions a appropriate chord locations

- While we still aren't there in having a full understanding of the various contributions to abrupt wing stall, this program was a major step in that direction.

Synergy in the Abrupt Wing Stall Program (AWS)

- AWS was result of F/A-18E/F wing drop effort
  - develop better understanding
  - identify techniques and figures of merit to predict
- Extensive use of both wind tunnels and CFD

Synergy in the Abrupt Wing Stall Program (AWS)

- Significant results

  - change to negative slope in wing root bending moment and lift curves

  - spanwise loading and the rate of change of spanwise loading with angel of attack

  - lateral activity on the Free to Roll rig

Synergy in the Abrupt Wing Stall Program (AWS)

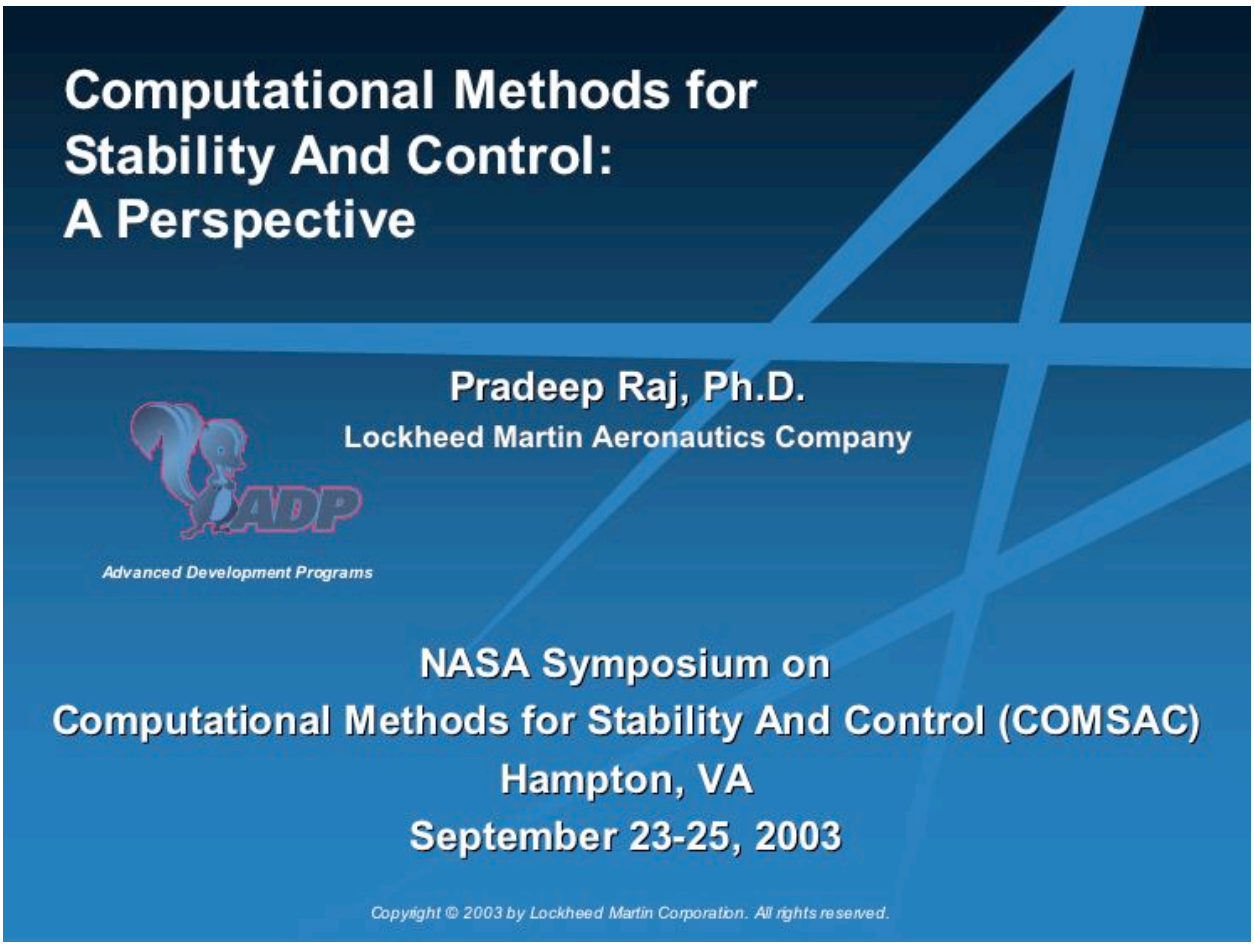
- measurment and calculation of steady and unsteady pressure distributions at appropriate chord locations

- AWS a significant step toward full understanding of the various contributors to abrupt wing stall

This presentation offers a perspective on the NASA COMSAC initiative from the vantage point of aerospace industry .

In this centennial year of Wright Brothers' "controlled" powered flight, it is rather fitting that we hold a symposium devoted exclusively to the problem of more effectively predicting stability and control characteristics of flight vehicles!

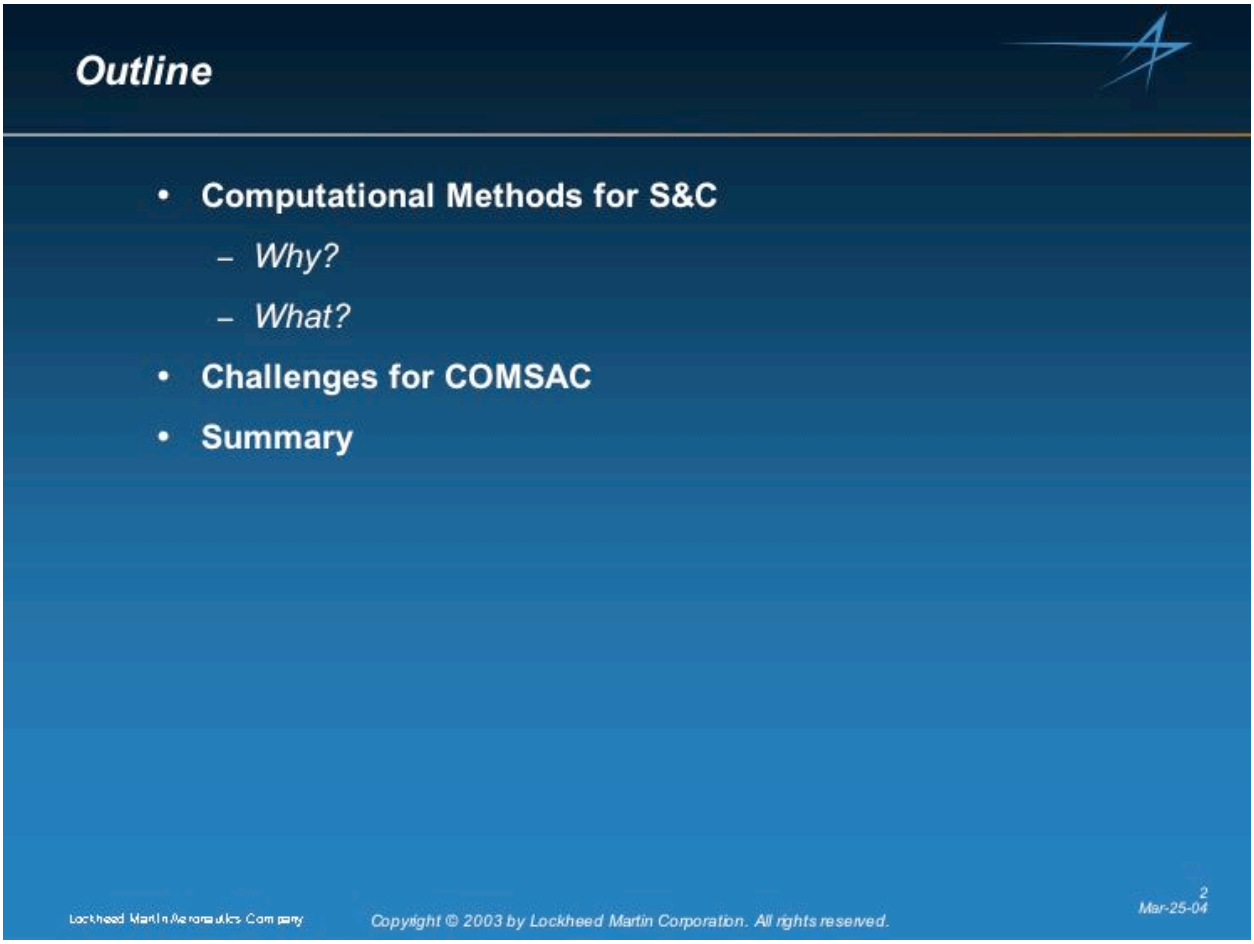
Although the symposium is limited in scope to only computational methods, resulting improvements in our ability to computationally predict S&C characteristics can have far-reaching implications.



The presentation starts out by highlighting the rationale and urgency for advancing the state of the art in computational methods for S&C.

A couple of examples are included to illustrate the capabilities and deficiencies of the current suite of methods.

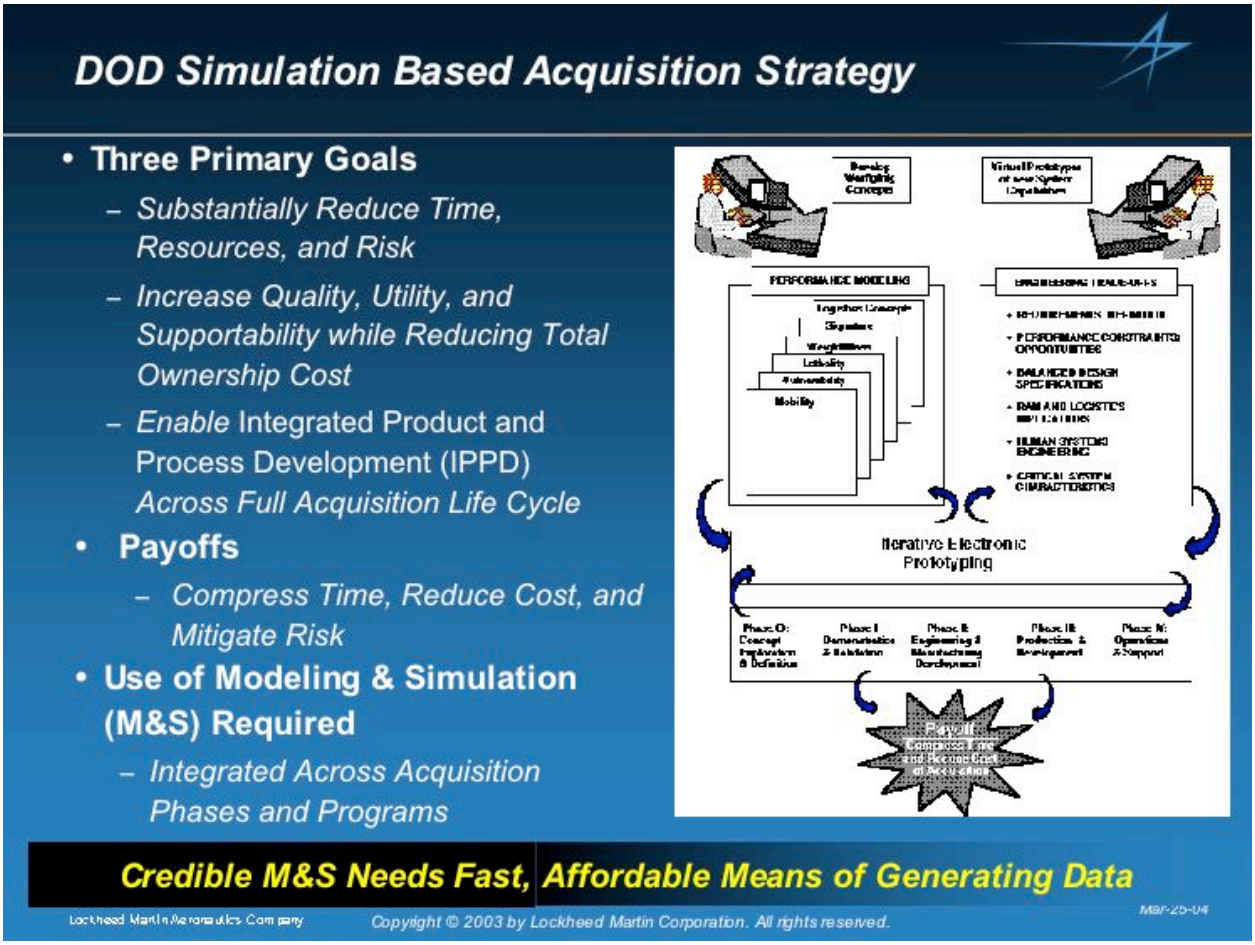
This is followed by a brief discussion of the challenges for the COMSAC initiative.
A summary chart concludes this presentation.



This chart outlines the primary motivation behind the need to advance the state of the art in computational methods for S&C.

The aerospace industry is deeply engaged in transitioning to a Simulation Based Acquisition strategy that the Department of Defense has adopted. Lockheed Martin is committed to implementing this strategy to meet customer expectations.

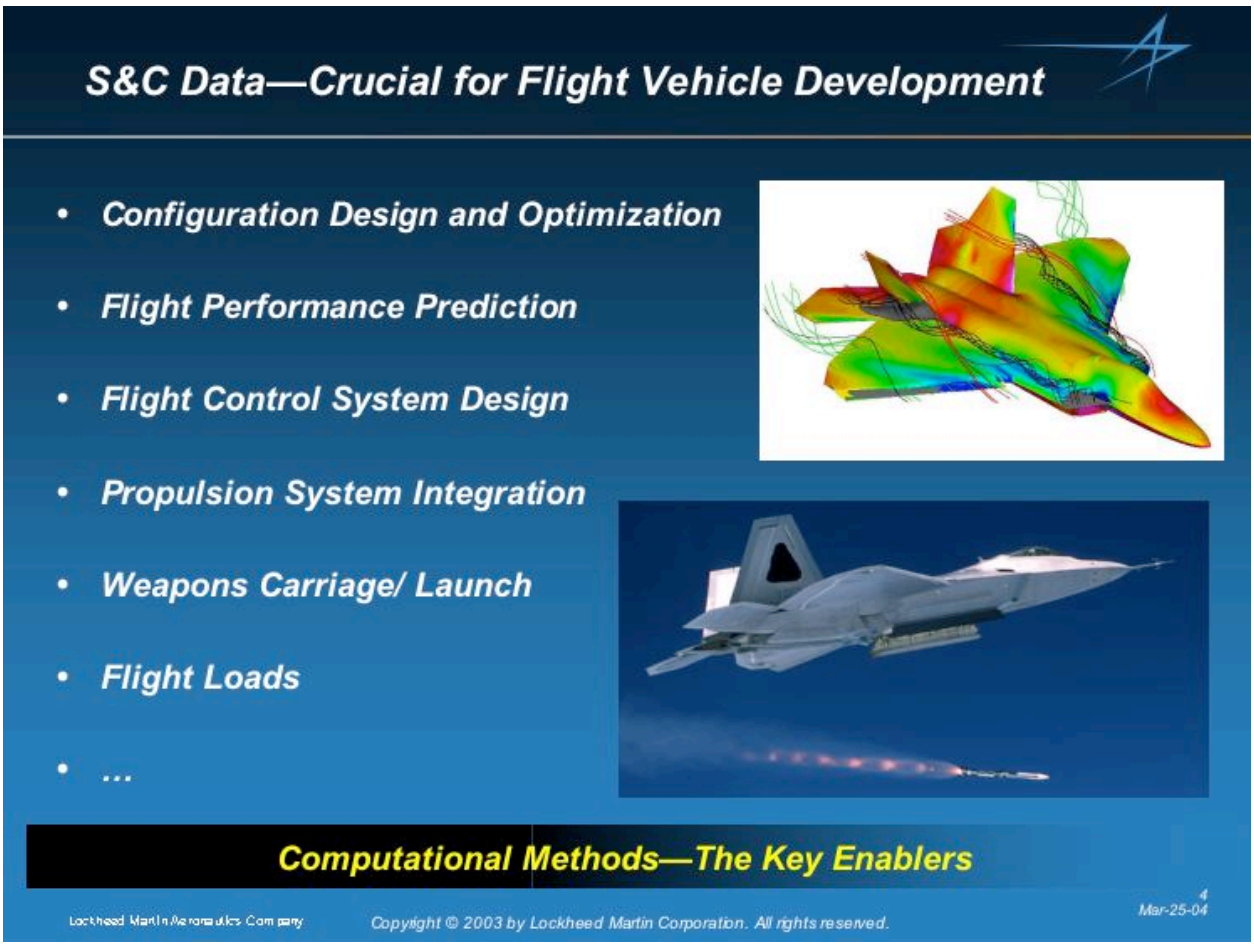
If successful, substantial benefits will accrue in quality and affordability of future flight vehicles for meeting national needs. However, realizing the benefits of this strategy depends on our ability to generate data in a timely and affordable manner to meet the demands of credible modeling and simulations.



A wide variety of data is required to support the Modeling and Simulation needs of a modern flight vehicle development effort.

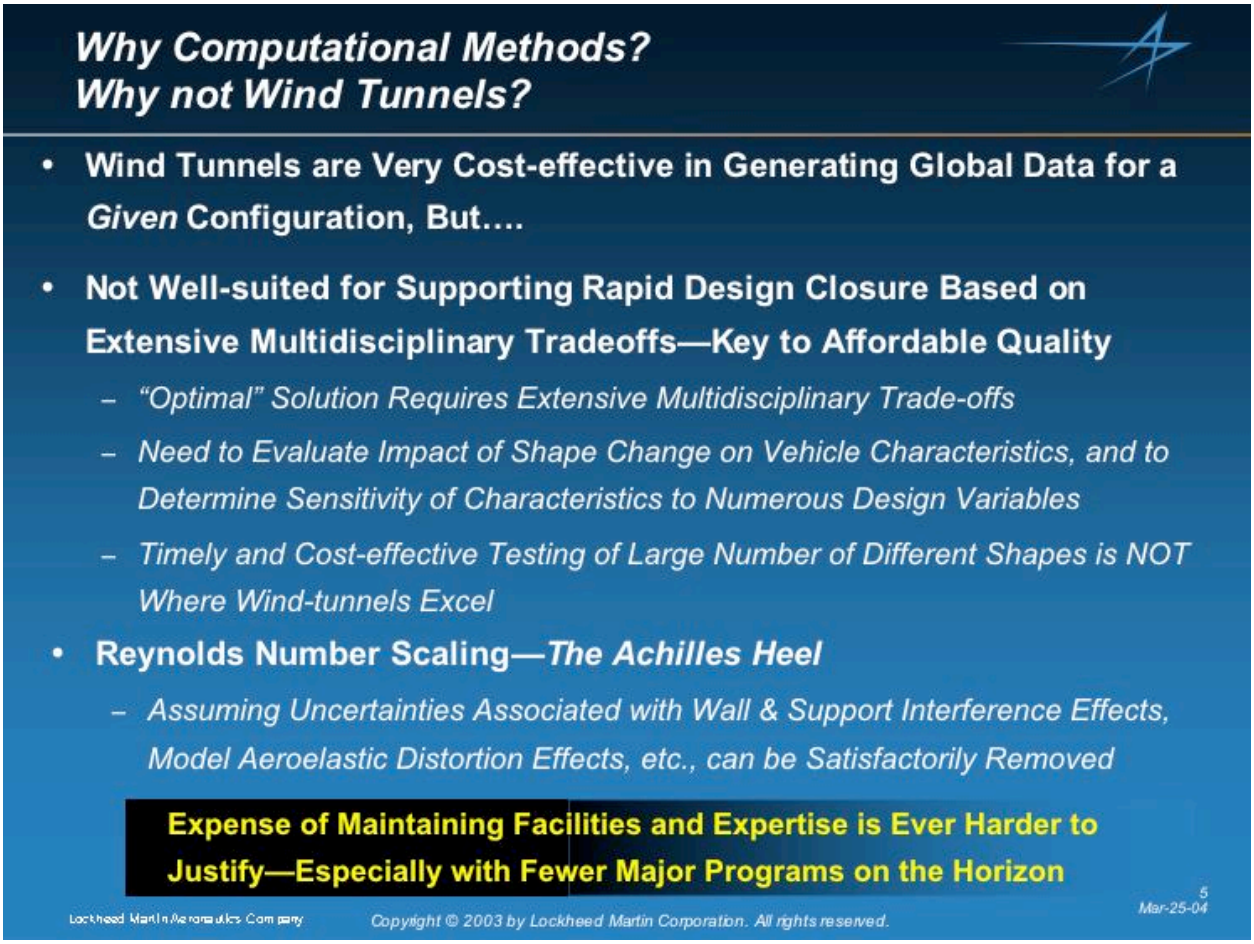
Stability & Control data is absolutely crucial because it has significant influence over decisions about numerous aspects of flight vehicle development, some of which are listed in this chart.

Computational methods are the key enablers for meeting the demands of S&C data.



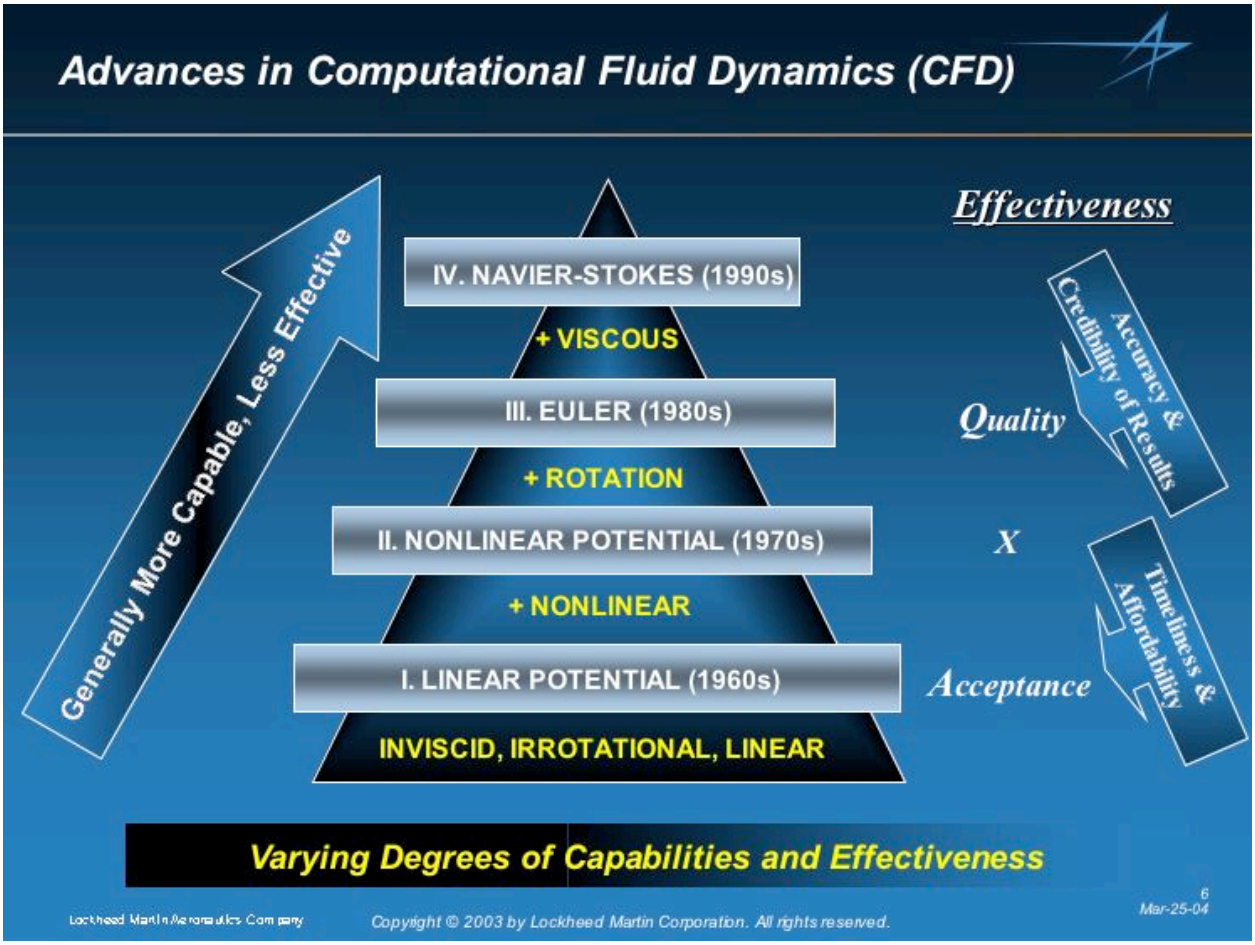
Since heretofore wind tunnels have been the primary means of generating S&C data for flight vehicle design, why not further improve the testing capabilities? Why should we look for computational methods as an option? This chart addresses these questions.
Although wind tunnels offer a proven and mature capability, they are deficient in supporting the demands of a M&S environment for successfully implementing the SBA strategy.

Reynolds number scaling is a fundamental limitation that plagues almost all wind-tunnel testing. Accurately predicting full-scale model characteristics using the measured S&C characteristics of a sub-scale model continues to be major challenge. This limitation, in principle, can be overcome by computational methods.



This chart summarizes the nearly four decades of focused development in producing ever more capable computational methods. The available methods can be generally grouped in four categories. As one moves up from the linear potential methods (Level I) to the Navier-Stokes methods (Level IV), there is a significant increase in capabilities resulting from the use of a more complete model of physics. However, the increased capability is generally accompanied by the penalties of much longer turnaround times and higher computer and labor resources. Consequently, all levels of methods are not equally effective for supporting the M&S demands.

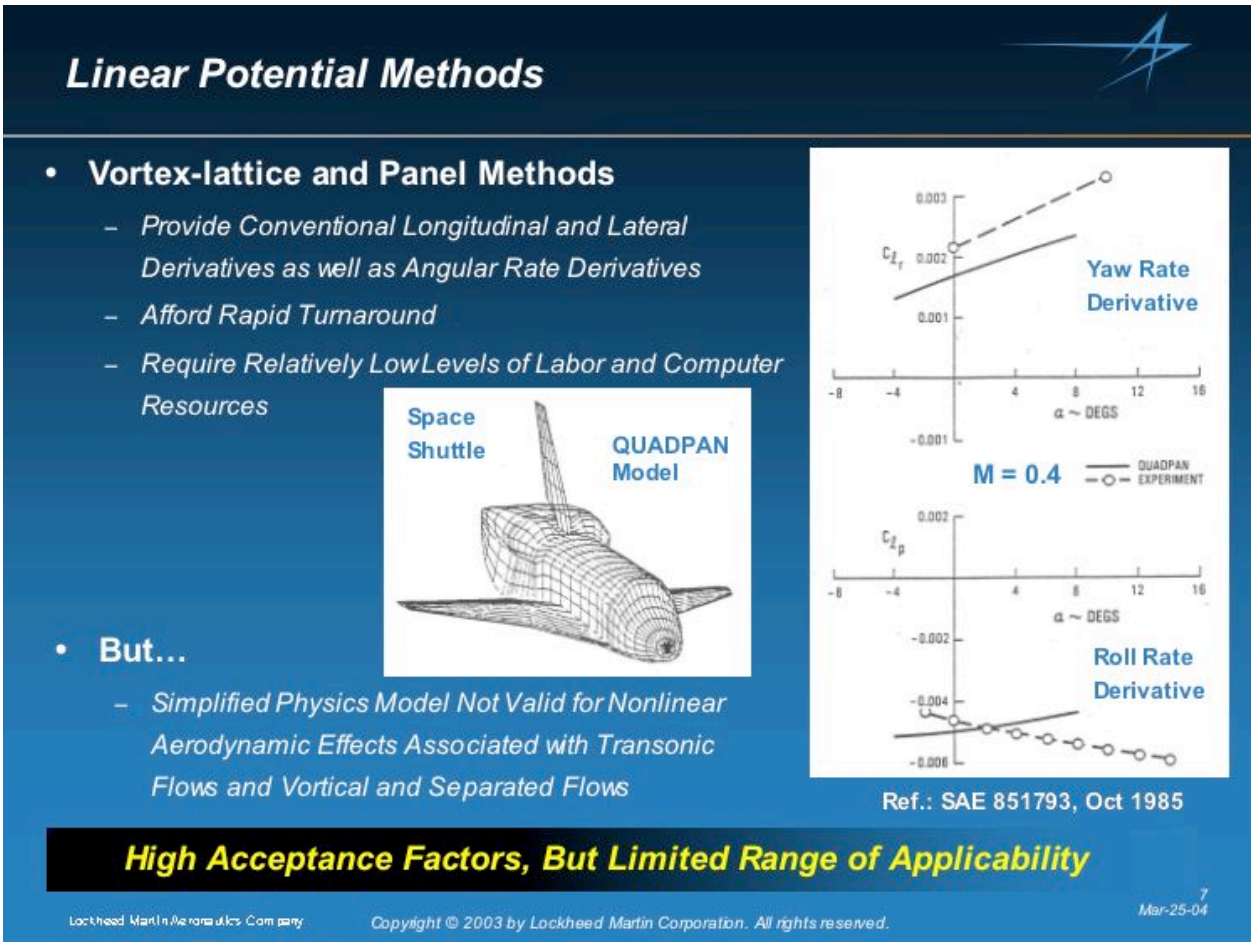
One way to assess the effectiveness of computational methods is to consider Effectiveness as a product of Quality and Acceptance factors (as shown on the right hand side of this chart). Accuracy and credibility of computational results are the primary Quality factors, and timeliness and affordability are the key Acceptance factors.



The next three charts illustrate the effectiveness of the linear potential and Euler methods that are presently in widespread use.

The linear potential methods used by Lockheed Martin fall in the category of vortex-lattice methods (using planar surface to represent geometry) and panel methods (using quadrilateral patches to approximate the actual geometric shape).
These methods are capable of generating S&C data including force and moment derivatives. Space shuttle data generated using our panel code, QUADPAN, is shown on the right hand side—excerpted from a SAE paper published almost two decades ago.

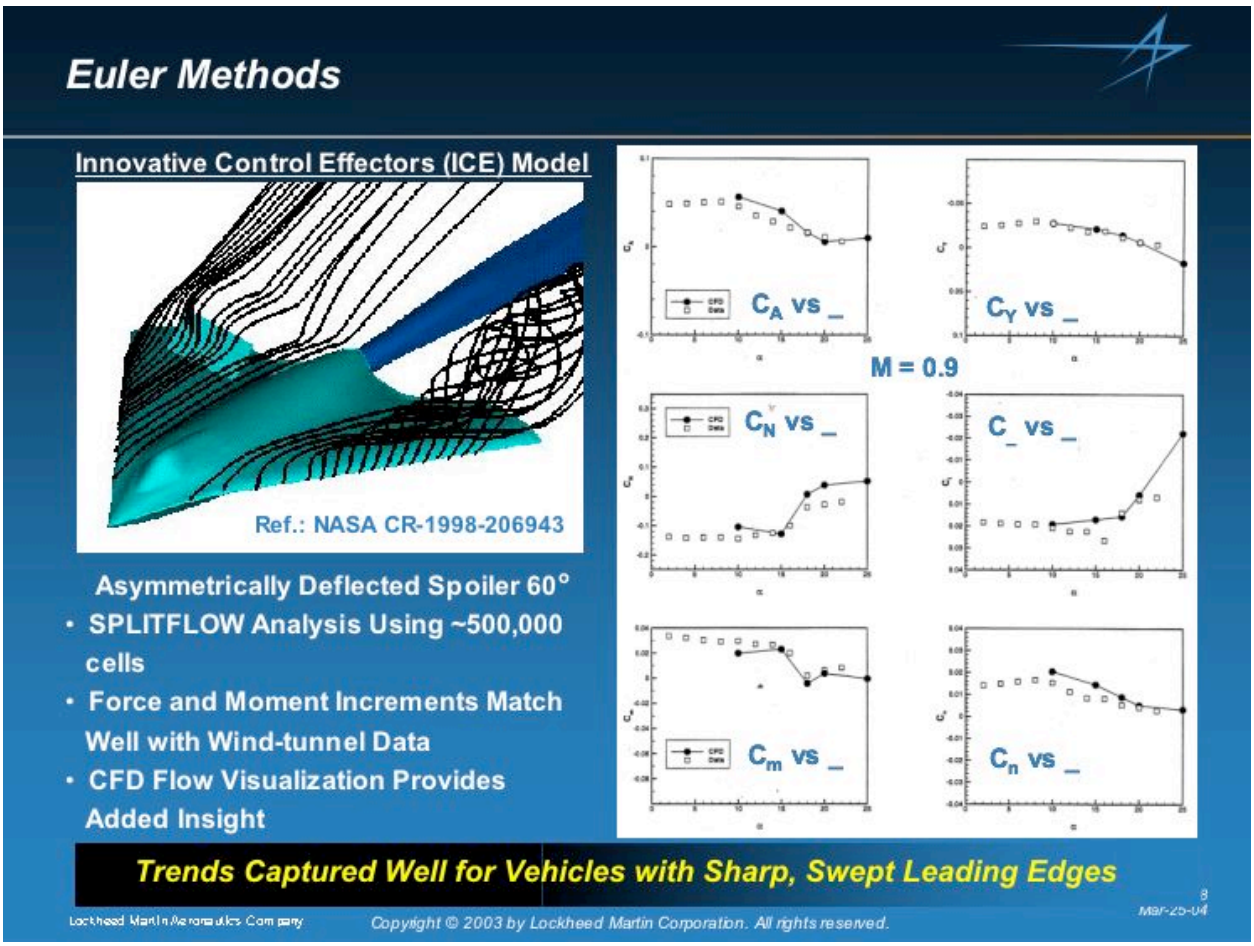
Due to the simplified nature of their flow physics model, the linear potential methods are not valid for analyzing nonlinear aerodynamic effects associated with shocks (transonic Mach numbers) and vortical flows (high angles of attack).



These methods afford rapid turnaround and require relatively low levels of labor and computer resources. Therefore, their Acceptance factors are high but the overall effectiveness is low except for limited regions of the flight envelope where the flows do not contain shocks or regions of separated flow.

As the Euler methods began to mature by the late 1980s, Lockheed Martin performed several in-house and NASA-sponsored studies during the 1990s to assess their capabilities and deficiencies for preliminary design applications. Part of the effort was devoted to examining the control effects. An extensive study was conducted for the ICE configuration using the adaptive Cartesian-grid SPLITFLOW code. The aim was to assess the code's ability to predict aerodynamic characteristics due to the deployment of leading-edge flaps as well as trailing-edge elevons and spoilers.

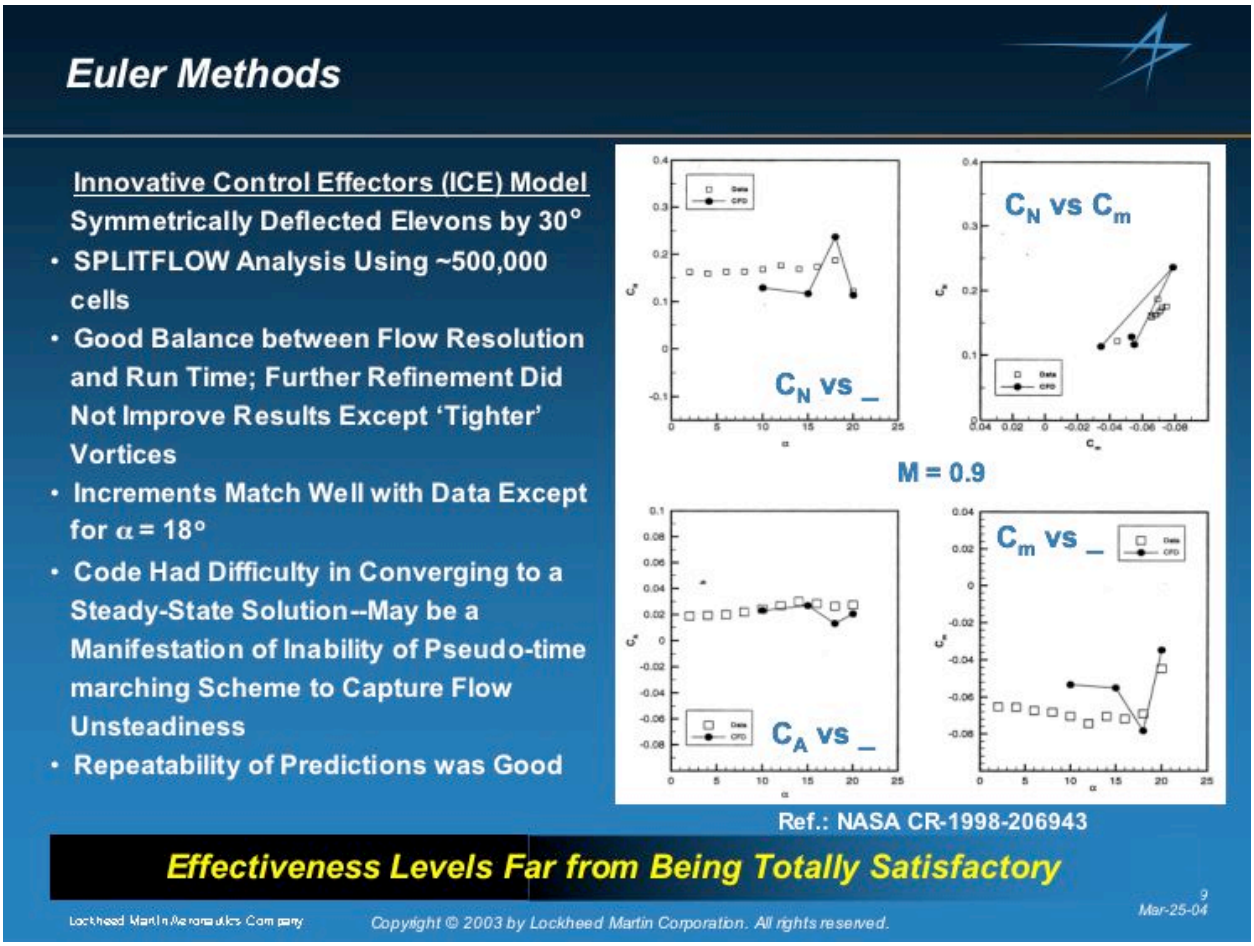
In general, the code captured the significant changes in flow characteristics and the trends of the force and moment increments. This chart illustrates the correlation of force and moment



increments for the 60° deflected spoiler case. Predictions for some angles of attack agree well with data while others do not. The side force and lateral-directional coefficients for this asymmetric deflection case show good correlation with data trends, except for the highest angle of attack of 25 degrees. One of the key benefits of computational methods is their ability to provide details of the off-body flow interaction which might have contributed to unanticipated changes in control effectiveness. Computational methods can provide advance warning of potential problems.

This chart shows results for the attached flow case for symmetrically deflected trailing-edge elevon on the ICE vehicle. The normal force (C_N), axial force (C_A) and pitching moment (C_m) increments due to deflection match quite well with the measured increments except at 18° angle of attack, where the code overpredicts the normal force and nose-down moment. On further investigation, it was found that for some angles of attack such as this, the solution had difficulty in converging and the force and moment predictions settled in at levels that did not correlate well with data. At other angles of attack both above and below the troublesome one, the solution proceeded much better in terms of convergence and predictions correlated well with test data.

Based on the results of the various studies, it could be concluded that unstructured-grid Euler



methods can be applied to predict control effects to support preliminary design of combat vehicles with sharp, swept leading edges. For configuration trade studies in early design stages, Euler methods are efficient given the substantial improvement in turnaround time and cost over viscous Navier-Stokes analysis by a factor of 3 to 5. However, the effectiveness levels are far from being satisfactory, and efforts must continue to render Euler and Navier-Stokes methods fully effective for preliminary design applications in an IPPD environment.

NASA's COMSAC initiative offers the right approach at the right time for advancing our capabilities in predicting S&C data using computational methods.
Ongoing advances in computers and algorithms may allow sufficiently rapid turnaround to produce a complete database in a timely manner.

Such a capability is essential to supporting the Modeling & Simulation needs of the SBA strategy that DoD and aerospace industry have adopted for future flight vehicle development.

However, one of the principal challenges facing the COMSAC suite of codes is to guarantee that the predictions faithfully represent reality. The traditional approach of validating computational

results with wind-tunnel data defeats the purpose—it adds time and cost! The COMSAC initiative must provide methods and techniques with a high level of Effectiveness.

This chart further outlines the challenges associated with achieving high levels of effectiveness.

A few key Quality and Acceptance factors are listed here that must be *simultaneously* enhanced to reach the desired Effectiveness targets.

Challenges for COMSAC

- **Quality**
  - *All "Key" Geometric Details and Flow Conditions*
  - *"Real" Flight Conditions*
    - **Aeroelastic Deformation**
    - **Power Effects**
    - **Complete Flight Envelope (Static and Dynamic)**
  - *Approach to Developing and Implementing "Validation Plan" for Each Application*
    - **Cannot Create "Validated Code" for ALL Applications!**
- **Acceptance**
  - *Ease of Use*
  - *Short Turnaround Time (Each Analysis and Complete Dataset)*
  - *Low Computational Resources (Time and Memory) and Labor Hours*
  - *Provisions for Software Portability, Upgradeability, Reuse*
  - *Plan for Timely Technology Transition/ Transfer*

Simultaneously Enhance Both Quality and Acceptance

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11
Mar-25-04

This chart lists several considerations for the COMSAC program plan to ensure that the program is able to deliver what it promises.

"Top Ten" Considerations for COMSAC Planning

1) Driven by End-user Requirements
2) Focused on Deliverables
3) Clearly Defined Product Features/ Characteristics/ Attributes
4) Phased Delivery Schedule
5) Effective Development Strategy
6) Sound Technical Approach
7) Credible Risk Assessment and Mitigation Approach
8) Measures of Merit for Assessing Progress and Capabilities
9) Well Defined Exit Criterion
10) Proper Matching of Development Plan and Available Resources

Promise What Can Be Delivered
Deliver What Is Promised

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12
Mar-25-04

In this presentation, a rationale was provided for the urgent need to develop computational methods for S&C.

The current state of the art was briefly discussed, and challenges for the COMSAC initiative were highlighted.

In moving forward, careful planning is critically important for maximizing the return on investment and to deliver what is promised.

Summary

- Computational Methods for Stability and Control are Key Enablers for Realizing the Full Benefits of the DoD Simulation Based Acquisition Strategy
- COMSAC Initiative is an Appropriate and Timely Response to Meeting the Need
- A Variety of CFD Methods are Available with Varying Degrees of Capabilities and Effectiveness
- COMSAC Must Strive for High Levels of Effectiveness
  - *Simultaneously Enhance Quality and Acceptance Factors*
- Careful Planning is Critical to Delivering What is Promised and to Maximize the Return on Investment

GO COMSAC!

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13
Mar-25-04

Boeing TacAir Stability and Control Issues for Computational Fluid Dynamics

23 September 2003

Bill Hollingsworth
Team Leader
TacAir Stability and Control

BOEING

Integrated Defense Systems

TacAir

TacAir Has Developed and Maintains Simulation Databases on Five Tactical Aircraft

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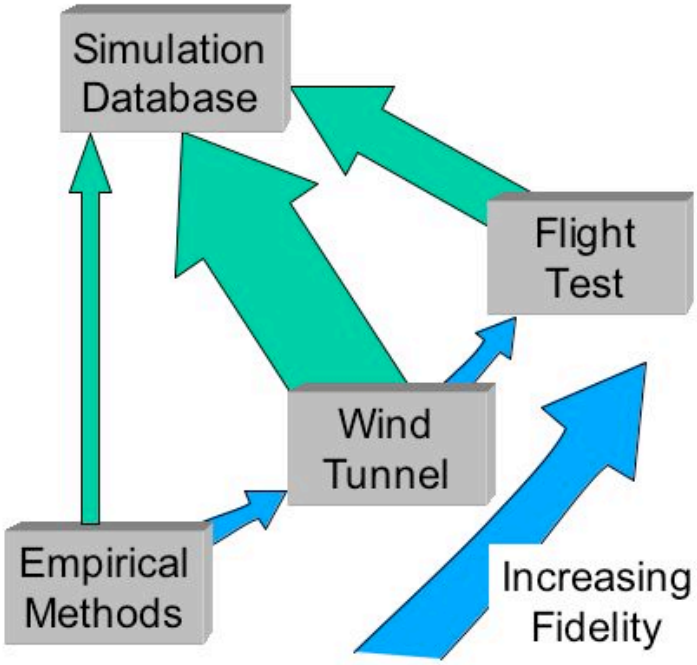
Integrated Defense Systems TacAir

CFD Not a Contributor to High Fidelity Simulation Database



CFD Not in Database Evolution Cycle

TacAir Uses
- Troubleshoot Isolated Flight Issues
- Guide Trade Studies

CFD Analysis

Why?
- Unvalidated For Issues of Interest
- Resource Demand

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TacAir

TacAir Experience in Aero Prediction Flags 5 Key Areas for Needed Improvement

Area	Symptom	Current CFD Usage
Basic Forces and Moments at High AoA	High AoA Wind Tunnel Characteristics not always Representative of Flight	Not Validated for High AoA. Not Used for Stability and Control Database.
External Store Effects	Store Interactions with Airframe and Other Stores Can Produce Localized Irregularities in Aero Characteristics Not Captured in Wind Tunnel	Used for Flow Understanding But Not for Aero Database Store Increments
Uncommanded Lateral Motion (Abrupt Wing Stall)	Lack of Validated Wind Tunnel Tools to Assess Abrupt Wing Stall Susceptibility	Steady State Solutions Used for Flow Understanding But Not Validated as an Abrupt Wing Stall Metric
Aerodynamic Damping	Reliable High Speed Values Difficult to Determine Prior to Flight	Not Used
Airframe Flexibility Corrections	Pre-Flight Predictions do not Agree with Flight Results	Low-Order Methods Used to Estimate Flexibility Effects

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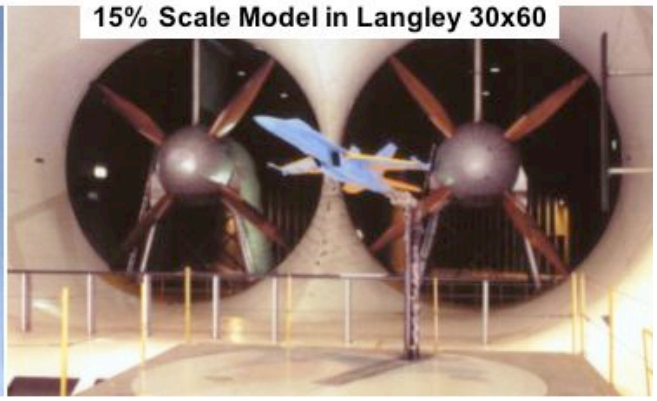
Large Tunnels and Models Not Definitive Predictor of High AoA Flight Characteristics



- Trend Has Been to Test Larger Models in Larger Tunnels to Increase Data Fidelity
- Wind Tunnel Database Sufficient for Flight Testing to Safely Commence …
- But to Fine-Tune Control Laws and Develop High Fidelity Training Simulation, Extensive Flight Testing Is Still Required

CFD Rarely Used for High AoA Evaluations

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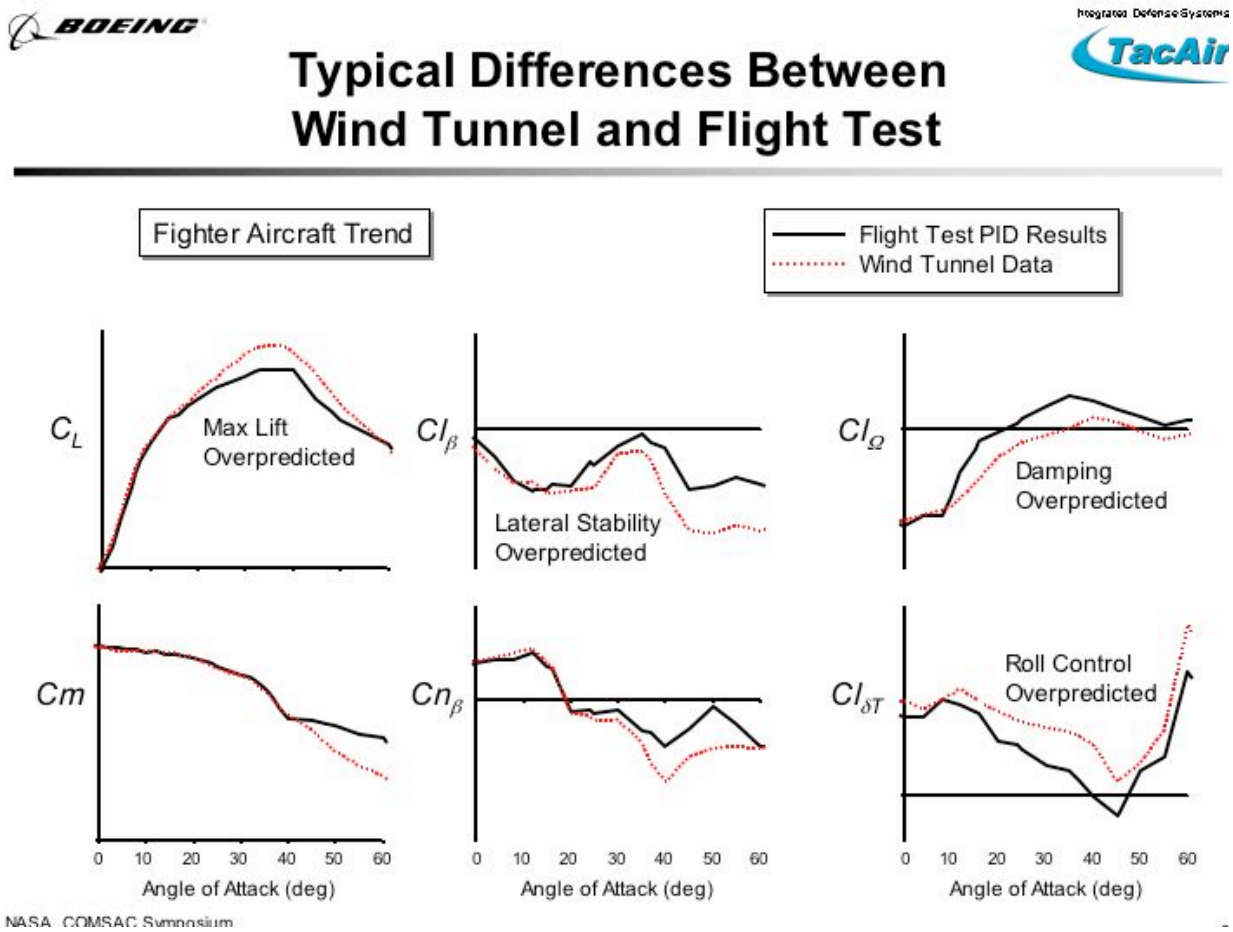
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Typical Differences Between
Wind Tunnel and Flight Test
Fighter Aircraft Trend
Flight Test PID Results
Wind Tunnel Data
C_L
Max Lift
Overpredicted
Cl_β
Lateral Stability
Overpredicted
Cl_Ω
Damping
Overpredicted
Cm
Cn_β
$Cl_{\delta T}$
Roll Control
Overpredicted
0 10 20 30 40 50 60
Angle of Attack (deg)
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Wind Tunnel Predictions of External Store S&C Effects not Always Accurate

Extensive High Speed Wind Tunnel Testing Performed to Document External Store Effects

These Wind Tunnel Store Effects on Airframe Stability and Control Can Be Inaccurate at Specific Transonic Conditions

CFD Used Sparingly to Evaluate High Speed External Store Effects

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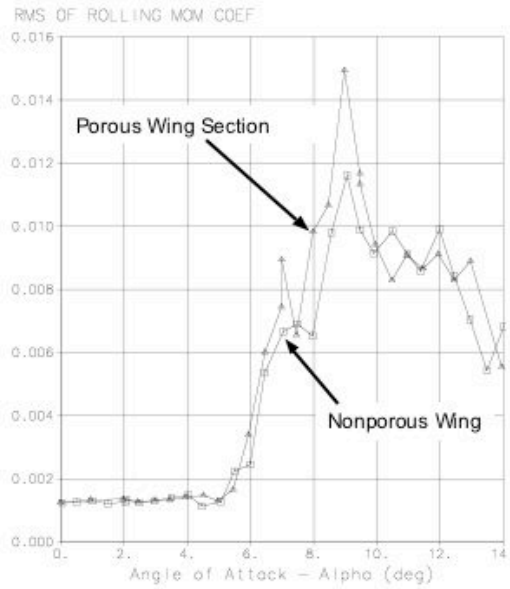
Potential for Uncommanded Lateral Motion (Abrupt Wing Stall) Difficult to Predict

- Significant Uncommanded Lateral Motion Was Experienced By F/A-18E/F During EMD Flight Test Program
- Wind Tunnel Testing Proved Inadequate for Finding Solutions
  - Nearly 100 Wing Modifications Evaluated In Wind Tunnel
  - Many Seemingly Promising Wind Tunnel Mods Failed In Flight
- Final Solution (Wing Surface Porosity) Determined Through Extensive Flight Testing.

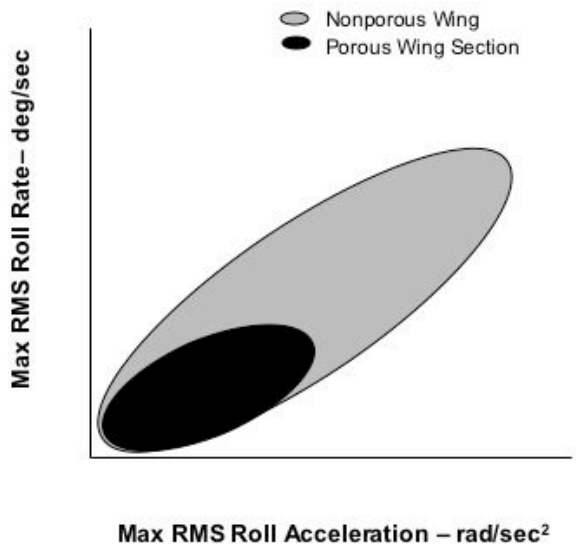
Steady-State CFD Employed to Understand Flowfield, But Abrupt Wing Stall Impact Difficult to Interpret

Wind Tunnel Results for Wing Fold Porosity Did Not Agree With Flight

Wind Tunnel Test of Wing Surface Porosity Showed Little Effect



Significant Reduction in Lateral Axis Motion Proven in Flight Test of Wing Surface Porosity



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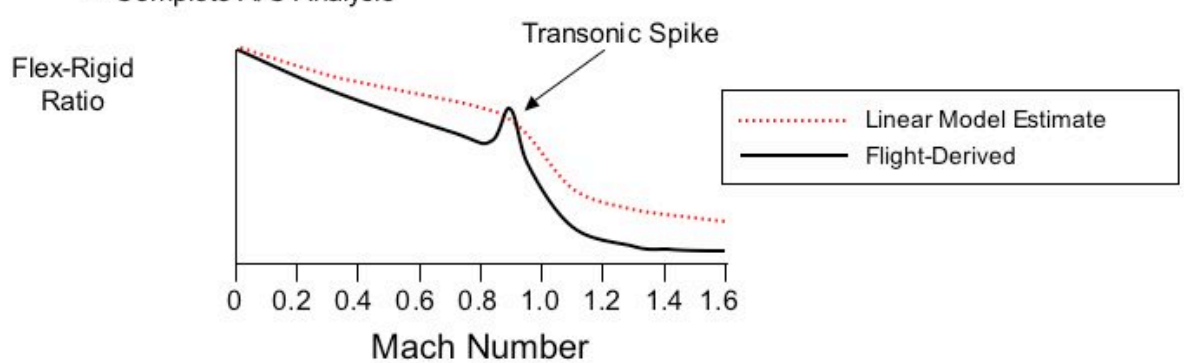
Dynamic Derivative Prediction

- Currently only Low Speed Wind Tunnel Facilities are available for obtaining Dynamic Derivatives
  - Rotary Balance Testing
  - Forced Oscillation Testing
- Applicability of Empirical Methods that are available (DATCOM, Wykes Strip Theory) to Modern Platforms is Questionable
- High Speed Derivatives are Extracted from Flight

CFD Not Used

Flexibility Effect Estimation Needs Improvement

- Current Methods of Predicting Flexibility Effects Employ Low-Order Aero/Structure Tools
- Challenges for CFD:
  - Non-linear Effects
    - Angle of Attack
    - Surface Deflections
  - External Store Effects
  - Complete A/C Analysis



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Recommendations for CFD Development for Stability and Control Applications

- Implement/Improve CFD Prediction Capability
  - High AoA Stability and Control Characteristics
  - External Store Aerodynamic Effects
  - Uncommanded Lateral Motion
  - Aerodynamic Damping
  - Airframe Flexibility Corrections
- Validate CFD Results Against Flight-Proven Data
- Provide Order of Magnitude Reduction in Required Resources Needed to Make CFD Use More Attractive
  - Turnaround Time
  - Computing Power
  - User Skill Required and Training Needed

NAVAIR S&C Issues For CFD

Steve Donaldson
Branch Head / Flight Dynamics
23 Sep 2003

NAVAIR

NAVAIR S&C Issues For CFD

- CFD can be a useful Tool for S&C Engineers
- However:
  - Its use has been limited to point designs
  - Primarily used for flow visualization
  - Has not been used to predict aerodynamics across the usage spectrum
  - The amount of data required for S&C analysis so far requires the use of extensive wind tunnel testing as the most efficient method of collecting aerodynamic data

NAVAIR

S&C Issues for CFD

- Methods to validate CFD codes are required for CFD to be a solution for the future
- Aero Engineers developing CFD methods must be completely familiar with the data needs of S&C Engineers
- Incremental build-up of CFD capabilities may provide the most realistic path for production of aerodynamic data

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Variables of Concern

- Control Surface Deflections
  - Leading Edge Flaps
  - Trailing Edge Flaps
  - Stabilators
  - Spoilers
  - LEX Vents
- Flight Conditions
  - Altitude, Mach, Airspeed, Alpha, Beta, etc.

NAVAIR

S&C Data Requirements

- Complete aerodynamic data must be compiled to understand the airframe aerodynamic characteristics. The control system must be robust and control effectiveness must be suitable for the air vehicle to manage both the aerodynamics and the inertia effects of the vehicle dynamics

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Some Recent CFD usages

- Provide Flow Field visualization
  - C-12 with a belly-mounted Sonobouy launcher
  - F/A-18 with the Sharp Pod (RECCE)
  - RC-26 with a modified fuselage Radome
  - F/A-18 Wing drop, ATFLIR, and TFQI
  - AWS program
  - F-35 jet effects
  - Recent effort to include M&S of Shipboard airwakes on the Flying Qualities during shipboard hover, landing and take-off tasks

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Near term CFD

- Benefit exists to do more comprehensive analyses for aircraft modifications
- Attempt to influence portions of the aerodynamic database
- Verify results/modify CFD approach
  - Requires a great deal of data to build confidence
  - Target aircraft where a great deal of "truth" data exists
- Embed CFD engineers with S&C personnel and vice versa. Common understanding of capabilities and needs must be identified.
- Identify the "Roadmap" for application of CFD to support S&C over the longer term

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Long Term CFD

- Provide force and moment coefficients where the wind tunnel is cost-prohibitive or technically challenged
  - Transonic dynamic derivatives
  - Jet effects
  - Hinge moments
  - Reynolds number effects
  - Complete vehicle grids
- Need to fully support the generation of a Stability and Control Analysis/Data Report

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An S&C Perspective on CFD

Russ Killingsworth
Lockheed Martin Aero
JSF Stability & Control

NASA COMSAC Symposium
23 - 25 Sep, 2003

Lockheed Martin Aeronautics Company

I will review the trends for wind tunnel testing since the Wright Brothers. Review data requirements for S&C. Show a few examples of CFD in challenging flow fields. Compare capabilities and time requirements for CFD and WT. And recommend the biggest payoff areas for applying CFD to S&C.

Outline

- Wind Tunnel Test Trends Since the Wright Brothers
- S&C Data Requirements
- Examples of CFD for S&C
  - Transonic, Low AOA, Zero Sideslip
  - Transonic, Elevated AOA with Sideslip
  - Post Stall, Low Speed
- Comments on CFD Process
- CFD Strengths
- Design Phase to Benefit Most from CFD Improvements
- Computing Power and Turnaround Time Trends & Status

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Objectives & Challenges

- Objectives:
  - Optimize the Design to Provide the Best Capability & Cost
  - Design & Fly Aircraft with No Surprises in Flight
- Complex Challenge to Predict Forces & Moments Before Flight
  - High Confidence in Linear, Steady Regions
  - Reduced Confidence in Non-Linear or Unsteady Regions
- Significant Past Examples of Surprises in Flight
  - Some Resolutions Very Expensive But Absolutely Necessary
- Increasing Expectations for Accurate Predictions at Lower Cost
  - Budgets are Pressured Down as Low as Possible
  - Surprises Can Add Huge Unexpected Costs, and Even Threaten a Program
  - Challenge to Find Balance

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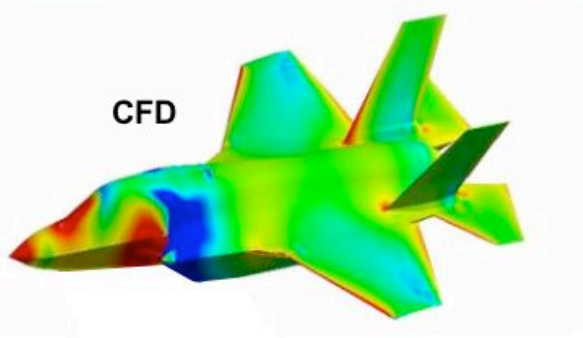
Tools for Predicting S&C Characteristics



Important Differences in Cost & Capabilities

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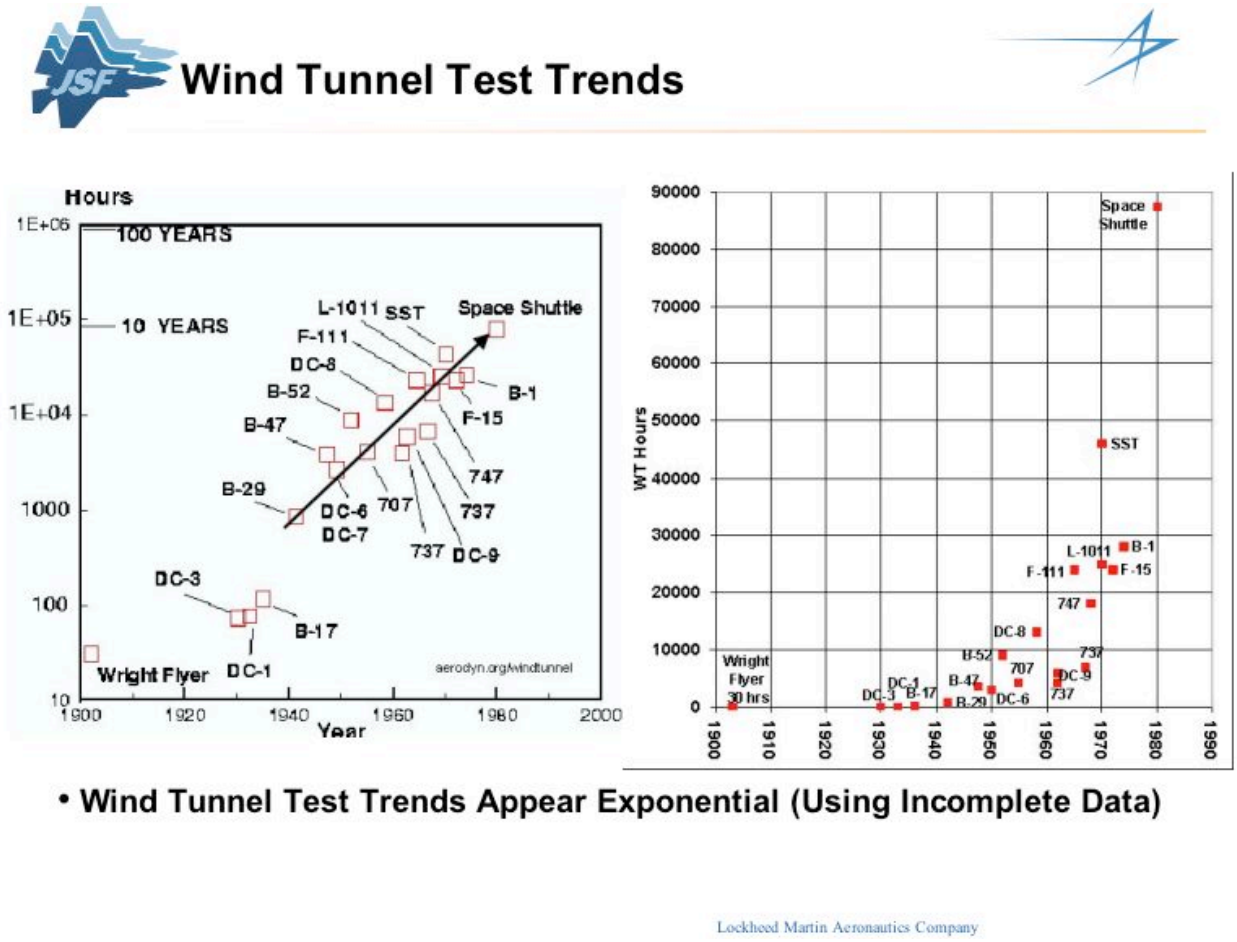
It would be nice to have a subscale model that could do everything that the full scale vehicle can do, except for Rn, but no model or tunnel can do all that. So we have to break up the terms into smaller pieces and test them individually and build them back up to represent the full scale aircraft at operating conditions. So we have models for basic, unpowered, static effects, then add inlet effects, jet effects, support system corrections, dynamic effects, etc. We measure component loads and hinge moments on yet a different model.

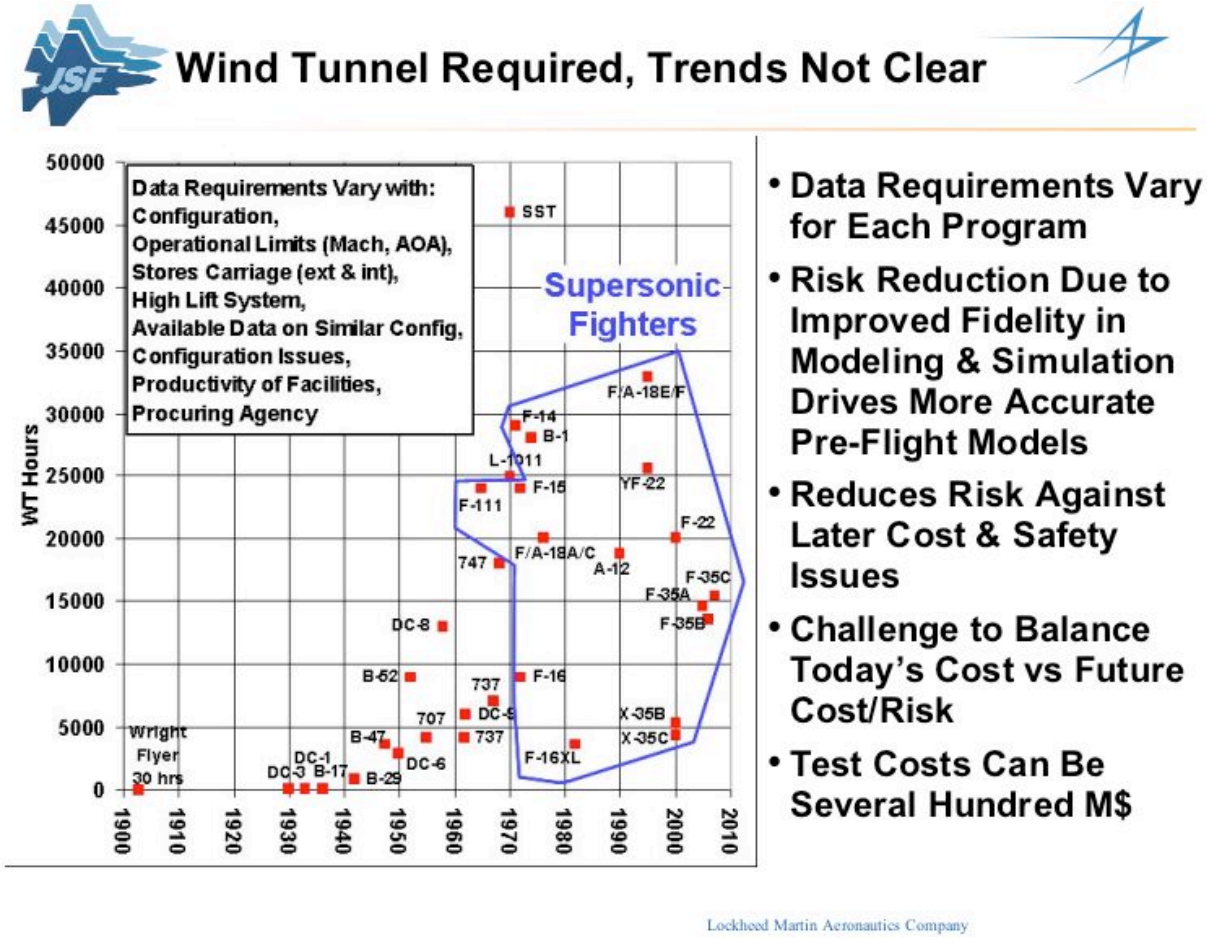
We have learned lessons from many generations of wind tunnel testing and the art has evolved to better represent the full scale aircraft. Many of these standard practices evolved from finding surprises in flight, and going back and figuring out why the surprises occurred. CFD doesn't have this experience yet in S&C applications.

I found the graphic on the left at a couple of web sites. It is wind tunnel hours on a log scale vs time since the Wright brothers. It indicates that WT test hours are growing exponentially. I made the plot on the right on a linear scale to illustrate the trend. But it is based on incomplete data and includes some special cases.



When I add more data points and focus on the range that doesn't include space flight, it shows that the trend is not exponential, but rather has a broad range, even for aircraft in the category of supersonic fighters.

It would be interesting to talk more detail about some of the examples, but we don't have time. A typical program today might take about 15,000 hours of wind tunnel time for one supersonic fighter aircraft.



This table is to compare the data requirements between performance and S&C.

Data Requirements for Performance & S&C

	3-DOF Perf Aero Database	6-DOF Aero Database
Products:	· Mission Performance · Basing Performance	· CLAW Design · FQ/S&C/HQ Analysis · Aircraft Limits · Actuator Requirements · Normal Procedures · Emergency Procedures
Coefficients	CL, CD, Cm	CN, CA, Cm, CY, Cl, Cn
AOA (Low Spd)	0 to Stall	-90° to +90°
AOA (Hi Spd)	0 to Stall/Nzmax	-10° to Above Stall/Nzmax
Beta (Low Spd)	n/a	-90° to +90°
Beta (Hi Spd)	n/a	±15° subsonic; ±10° supersonic
Controls	Sym HT for Trim LEF & TEF On Sched	All Possible Control Positions, Both On & Off Schedule, Including Failures
Mach	· Basing: Mach 0.2 · UA: Mach 0.6 to Max	Operational, Service and Permissible Envelopes
Flexibility	none	Full Effects throughout envelope
Dynamic Aero	Cmq from 6-DOF	Full Effects throughout envelope
Gear Baseline	Gear Dn + Increments	Gear Up + Increments for Down
Ext Stores	CL, CD, Cm	Full 6-DOF effects thoughout envelope, Gear Up and Down
Wep Bays	STOVL baseline open CTOL/CV not modeled	Full 6-DOF effects in all modes and all door usage
Hinge Moments	n/a	Full hinge moment model of all control surfaces
Real Time Sim	n/a	Yes

- 3-DOF & 6-DOF Databases Are Developed to Serve Different Purposes
- Each Must Accurately Represent Aero, But with Different Focuses & Scope
  - Performance Accuracy Reqd at Cruise, Vmax, Maneuver, TO&L
  - S&C Accuracy Reqd Throughout Envelope, including Failures
- Coordination is Done to Ensure Consistency
- Timing of 6-DOF Database Lags 3-DOF Due to Complexity Differences

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Some aero data is easy to predict, others are challenging. The most challenging is combinations of challenging conditions, such as

Stability & Control Challenge

	"Easy"	Challenging	Most Challenging
AOA	Low	Moderate	Stall, Post-Stall
Mach	Low	Supersonic	Transonic
Sideslip	Zero	Small	Moderate, Departure
Control Defl	Zero	Small	Maximum Effectiveness
Stores	None	Simple	Full Geometry
Aeroelasticity	Rigid	Linear	Non-Linear FEM & Aero
Jet(s)	Off	On/Varying	
Inlet(s)	Off	On/Varying	
Ground	OGE	IGE conventional	IGE STOVL
Failures	None	Non-Aerodynamic Geometry	
	Individual		Combined

- **Most Complex is Combined Non-Linear, Complex Flow Conditions**
  - **Transonic Mach, Elevated α, Non-Zero β, Stores, Low Altitude**
  - **Stall/Post-Stall, Large β, Stores, Power, Inlet**
  - **STOVL Ops (Inlet & Jet), Near Ground, Crosswind, Stores, Elev α**

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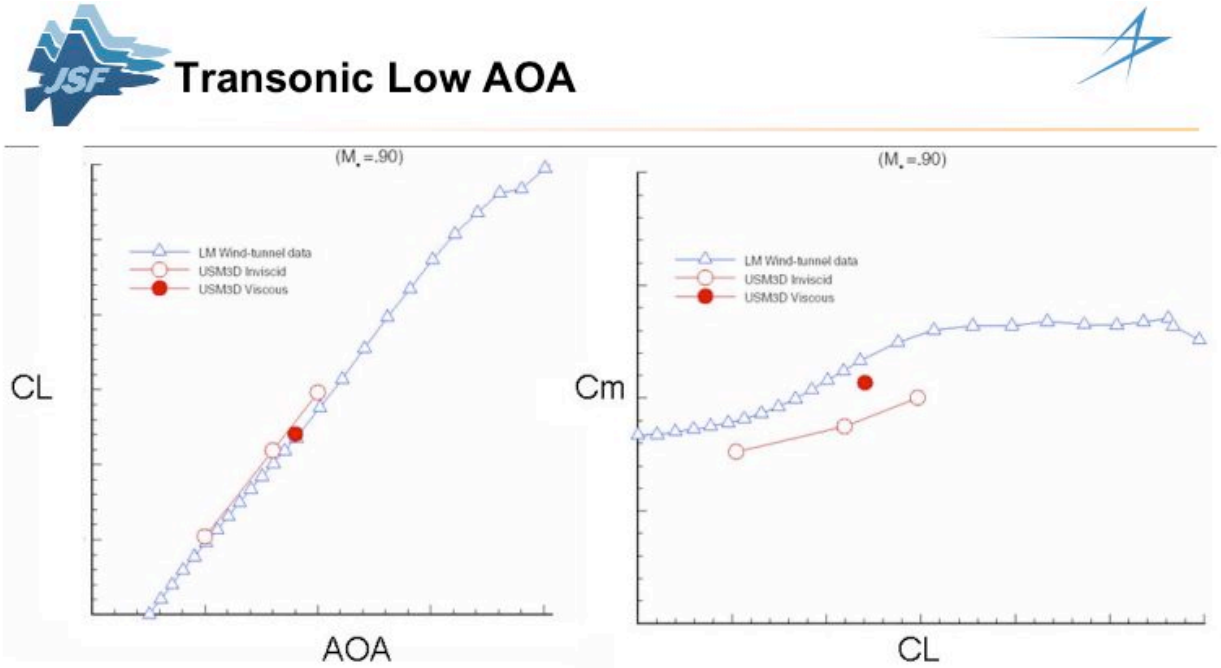
Here is an example of CFD predictions at Mach 0.9 for low AOA lift and pitching moment. Inviscid CFD showed good trends, but an offset. Viscous CFD got closer to the correct absolute answer.

The next step would be to refine the grid and possibly the turbulence models to get a better answer.

I think that CFD can match wind tunnel data at low AOA given time and given the WT data. But without the WT data, you can't be sure you have the right answer.

Once you calibrate the CFD to the WT data, you then have a set of parameters for the specific CFD tool that can be used to look for incremental changes to the vehicle and to understand the flow physics.



- **CFD Can Match Most Wind Tunnel Data at Low AOA Given Time and Given Wind Tunnel Data**
- **Matching Wind Tunnel Data Calibrates the Method, Grids, & Turbulence Models Which Allows Further CFD to Predict Incremental Effects & Understand Flow Physics**

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I will show CFD to predict transonic characteristics at elevated AOA and beta. This is a particularly challenging condition because it includes a mixture of strong shocks, strong vortices, regions of separation, and unsteady flow. And the situation is even more complex because this flow also varies with Mach, aoa, beta, tef, ht, stores, probably rates, probably altitude due to aeroelasticity. This challenges both WT and CFD.

Transonic Aero at Elevated α & β

- Very Complex Flow at Elevated α & β
  - Strong Shocks, Strong Vortices, Separation, Unsteady
  - Varies with Mach, α, β, δ_{LEF}, δ_{TEF}, δ_{HT}, Stores, p?, q?, r?, Altitude/Flex?
- Static Wind Tunnel Testing Applies Well to Steady, Stable Flow
- CFD Provides Insight to Flow Physics Given Test Data as Guide

Challenges Both WT & Computational Methods

Force & Moment Characteristics Well Behaved at This Condition

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Our objective was to improve lateral stability.

CFD Example for Transonic Lateral Stability

- **Objective: Improve Transonic Lateral Stability**
- **Approach**
  - **Use Navier-Stokes to Predict Lat-Dir Trends from Wind Tunnel**
  - **Identify Flow Characteristics & Root Causes**
  - **Evaluate Cl_β and Performance Points**
- **CFD Tasks Completed**
  - **Developed Initial 6M Cells (LEF/TEF=10/0 and 10/10)**
    - Inadequate Correlation with Wind Tunnel
  - **Increased to 12M Cells (LEF/TEF=10/0 and 10/10)**
    - Improved surface and off-surface wing resolution
    - Resolved outboard LE/TE flap gap details
    - Improved Correlation at TEF=0, But Opposite Trends with δTEF
  - **Increased to 18M Cells (LEF/TEF=10/10)**
    - Clustering cells on the LE, and at hingelines
    - Refined inboard TE flap gap details
    - Removed near-body non-point-to-point interfaces
    - Improved Correlation (Same Direction, Smaller Magnitude)

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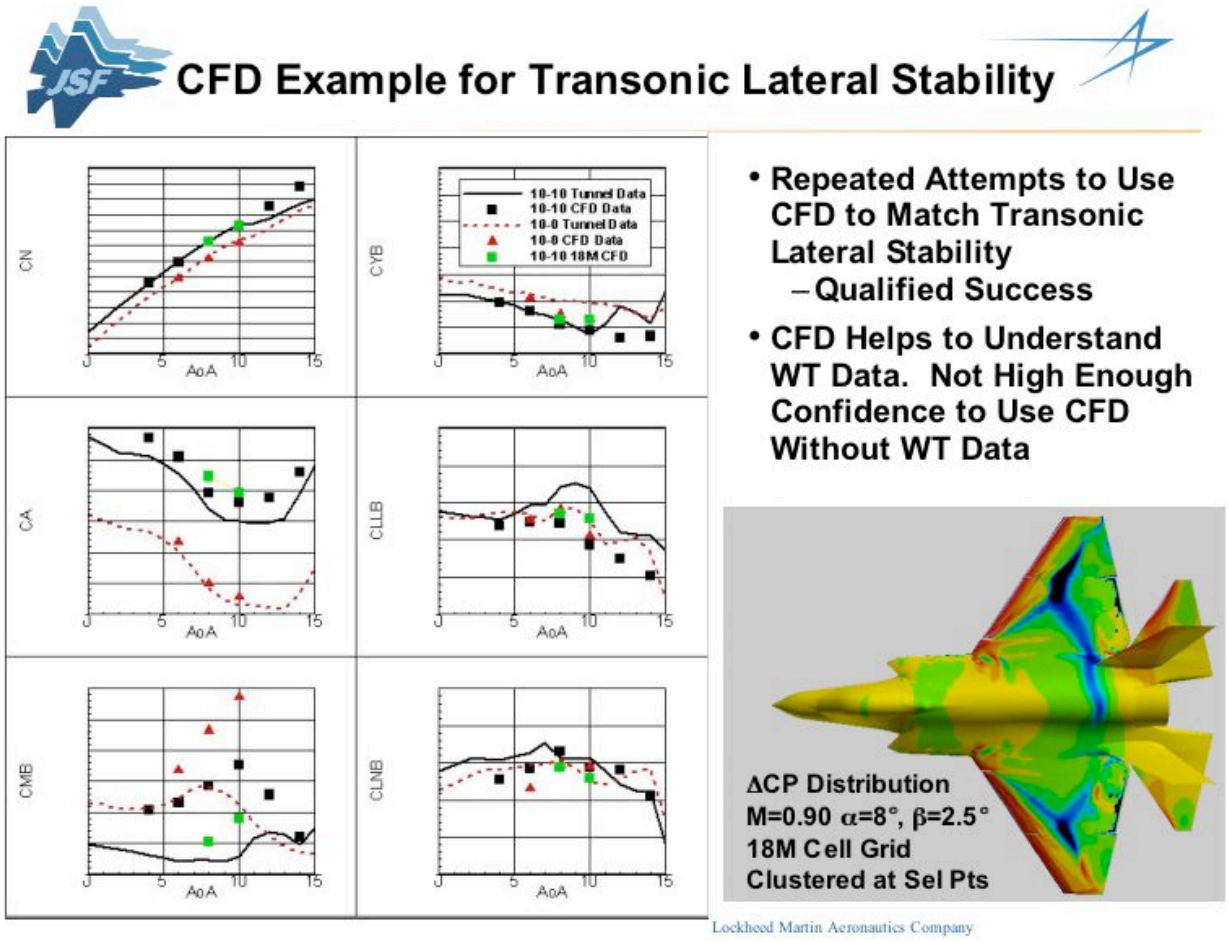
We started off with 6M grid cells but did not match well enough. We double the cells and got better correlation, but still had opposite trends with TEF. We tripled the cells to 18M and got improved correlation but still not matched. Some coefficients were still substantially off, even for incremental effects.

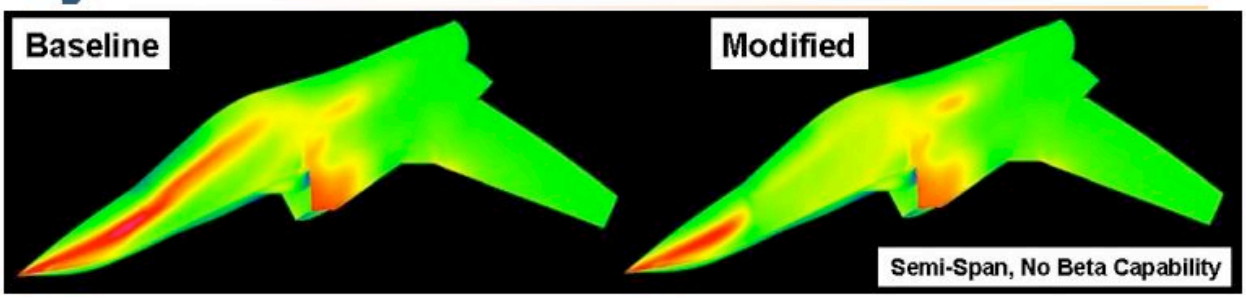
So this illustrates my point that CFD can try various levers to improve correlation with WT and may get to a match, given time and given the WT data, but can't be relied on to get the right answer without the WT data.

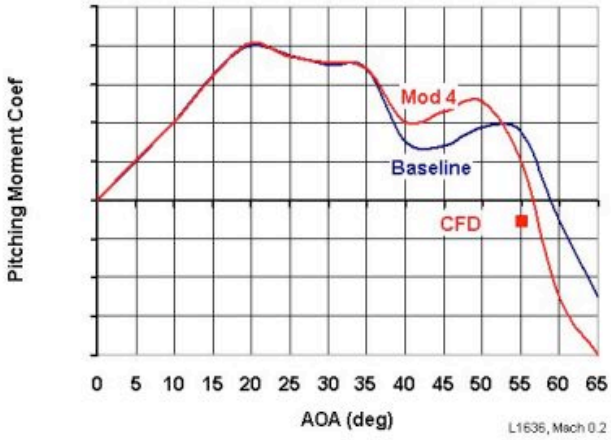
It is still worthwhile to do since it provides understanding of flow physics, and provides a tool to look at effects of small changes.



Here is an example of CFD at high AOA at low speed. Our objective was to find nose down pitching moment at 55 deg AOA. CFD showed forebody changes that could provide nose down Cm or -0.046. We tested several changes similar to the CFD recommended geometry. Some of them provided nose down at 55 aoa, but all of them also had nose up at lower AOA, which moved the critical point to a lower aoa and provided no benefit. If we had time to work this further, we might have been able to find a successful change, but time and money ran out.

CFD Example for High AOA





- Objective was Nose Down Cm
- Pre-Test CFD Showed Nose Down Benefit of -0.046 ΔCm at 55° AOA
- Wind Tunnel Test Showed Nose Up Penalty of -0.015 ΔCm But +ΔCm at Intermediate AOA, Moving Critical Point
- Further Calibration & Refinement Could Improve Method & Provide Important Benefits
- Time & Money Ran Out

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High AOA Aerodynamics

- Even After Extensive Pre-Flight Wind Tunnel Testing, High AOA Characteristics Always Require Updates After Flight Test
  - Adds Cost & Risk to High AOA Flight Test Programs
- Matching High AOA Static Characteristics is Not Simple
  - Many Corrections Needed From Sub-Scale Models to Flight
  - Support System, Model Geometry for Support, Jet-Induced Aero, Inlet-Induced Aero, Reynolds Number, Direct Thrust, Inlet Momentum
- Matching High AOA Dynamic Characteristics is Even Harder
  - Reynolds Number
  - Transition
  - Sub-Scale Test Methods & Modeling Need to Match Flight Dynamics
  - Many Aircraft Have Important Time-Dependent Aero Effects Near Stall or in Post-Stall Flight
- Improvements are Needed for High AOA Predictions
  - Wind Tunnel Test Procedures & Capabilities
  - CFD with Validation

My experience with CFD process is:

CFD Process for S&C

- Start with Wind Tunnel Data (F&M, Cp, Flow Vis)
- Build Grid of Configuration Tested
- Decide Turbulence Model
- Run CFD Solution to Convergence
- Compare Solution to Wind Tunnel Data (F&M, Cp, Flow Vis)
- Iterate on Grid Density, Grid Pattern, & Turbulence Model Until Correlates with Wind Tunnel
- If Correlation Still Not Adequate, Move Up to Unsteady CFD Solution & Repeat CFD Calibration
- Once Correlation is Adequate, Declare Successful Prediction
- For Predictions on Alternate Geometry or Conditions:
  - Build Grid Model of Alternate Geometry or Condition
  - Run CFD Using Same Grid Density, Pattern, Turbulence Models from Calibrations Above

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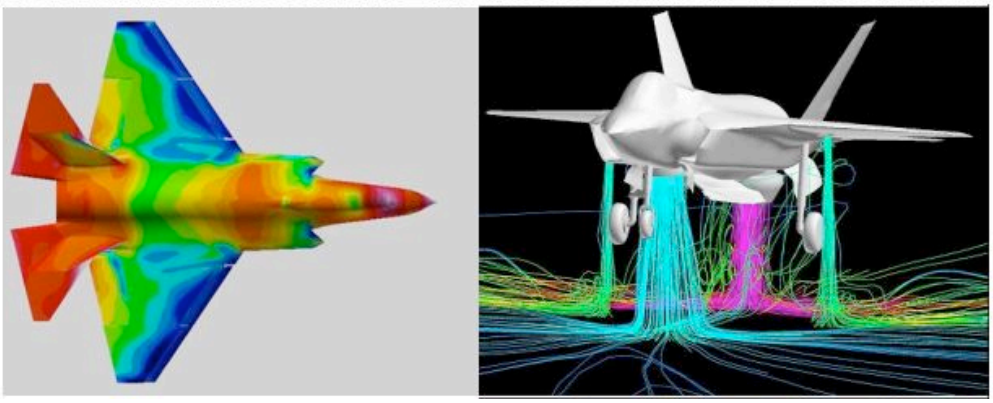
So to summarize my examples, there are some flow conditions of great interest that are challenges to CFD.

Important S&C Concerns are Challenges to CFD State-of-the-Art

- **Most Challenging Flow Conditions:**
  - Transonic, Unsteady Flow at Elevated AOA & β (Static & Dynamic)
  - High AOA Static & Dynamic Characteristics
  - STOVL Mode in Ground Effects (Multiple Jets, Multiple Inlets, Crosswind, Ground)
  - Transonic Effects of Stores, incl Interactions on Controls, β
  - High Lift Mode Non-Linearities in AOA, β, Control Effectiveness
- **CFD Can Visualize Flow & Can be Calibrated for F&M, But Can't be Relied on for F&M for Most S&C Without WT Test Results**



But CFD is a tremendous tool. Future benefits to S&C could be as significant if we get to work using it, learning the capabilities, finding out how to get increased confidence. It has been used successfully for:

CFD Strengths

- Drag Optimization
- Selected Data for Conceptual Design
- Incremental Trade Studies
- Quantify Effects Not Achievable in Wind Tunnel
- Improve Understanding of Complex Flow Fields

- Tremendous Benefits Have Been Derived from Applying CFD to Configuration Optimization for Performance
- Future Benefits to S&C Could Be As Significant

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Requirements vary by program phase.

S&C Needs for Aerodynamic Data Vary With Program Phase

- **Conceptual Design Requires Rapid Preliminary Aero**
  - **CFD Accuracy is Good for Conceptual Design, but is Too Slow**
    - Set Up, Grid, Sideslip, Control Deflections, Config/Stores
  - **Need Rapid 6-DOF Database (sideslip, control effectiveness)**
- **Configuration Development Requires More Accuracy & Much More Data**
  - **Configuration Optimization**
  - **Configuration Decisions Require High Confidence**
  - **Find & Resolve Configuration Problems As Fast As Possible**
  - **Wind Tunnel Testing Required**
  - **CFD Can Identify Trade Studies to Run in Wind Tunnel**
- **Preparing for Flight is the Most Demanding**
  - **Very Extensive Aero Database Required**
  - **High Accuracy Required to Avoid Surprises (Cost, Safety, Schedule)**
  - **Only Wind Tunnel Testing Has Proven Adequate**
  - **CFD Can Provide Understanding of Complex Flow Characteristics**

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This is my experience in the use of CFD and wind tunnel for performance and S&C by program phase. We mostly use the wind tunnel, but also use some predictive methods in all phases.

Current Typical Aero Prediction Usage

- **Map Current Procedures to Identify Opportunities**

	Computational Methods				
	Linear	Non-Linear Euler	N-S	Wind Tunnel	
Conceptual Design					
Performance		Varies	Varies	Minor	• Selected Specs (Cruise, Vmax) • CFD Does Not Provide Adequate Confidence for Landing Perf
S&C	Minor			Minor	• CFD Too Slow for S&C - OML Changes for Performance before Grid Set Up for Beta, Control Deflections, etc
Preliminary Design					
Performance		Extensive	Varies	Extensive	• Wind Tunnel Often Confirms CFD for Cruise, Vmax, But Many Examples of Differences • Configuration Decisions Require High Confidence, Which Requires WT Data
S&C	Minor	Minor		Extensive	• Only Wind Tunnel Provides High Enough Confidence for Configuration Decisions
Detailed Design					
Performance		Loads	Trades	Extensive	• Only Wind Tunnel Provides Enough Confidence for Major Perf Requirements • CFD Used Where WT Cannot Support (Secondary flow, Support, Wall, etc)
S&C	Minor (Flex)	Minor	Issues	Very Extensive	• Only Wind Tunnel Provides High Confidence & High Volume of Data for Flight Prep

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The biggest payoff for CFD would be in conceptual and preliminary design, where the most important configuration decisions are made.

Design Phase for Most Benefit from CFD

- Biggest Payoff from Using CFD for S&C Would be in Conceptual and Preliminary Design Phases
  - Most Far-Reaching Configuration Decisions are Made Early
  - Control Sizes Change in Pre-Design, But Rarely are Controls Added or Deleted and When That Happens in Pre-Design, it is Costly
- Conceptual Design Requirements
  - Basic Longitudinal & Lat-Dir Stability & 3 Moment Control Power
  - Fast Data to Support Configuration Options
  - Accuracy Can be Reduced (~20% ?)
- Preliminary Design Requirements
  - Basic Longitudinal & Lat-Dir Stability & 3 Moment Control Power
  - Accurate Enough to Freeze Control Sizes (Need Control Power <u>at Max Deflections</u> to be Within 10%)
- CFD Would Have to Improve Both Confidence & Speed to Support S&C in Conceptual or Preliminary Design

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To summarize the benefits of applying CFD to S&C.

Benefits of Advancements in CFD for S&C

- Aircraft Capability
  - Knowing Characteristics in Design Stage Allows More Optimization
  - Optimization Reduces Cost to USG Customer. Small Recurring Benefits Provide Extremely Large Reductions in Life Cycle Cost.
- Developmental Cost & Schedule
  - Improves Efficiency of Configuration Optimization, Increasing Aircraft Capability, Improving Cost & Effectiveness for Customer
  - Allows Focusing Wind Tunnel Testing on Critical Areas
- Flight Test Cost
  - Reduce or Prevent Discovering Important Differences in Flight
  - More Rapidly Resolve Issues Which Do Occur
- Safety
  - Safety is Hampered by Unexpected Non-Linear Characteristics, Which Also Represent the Greatest Challenges to CFD
- All Aspects Above Drive Cost to USG Customer / User
  - Potential to Reduce Wind Tunnel Costs, But Increase Costs for CFD
  - Life Cycle Cost Benefits Could be Hundreds of Millions of Dollars

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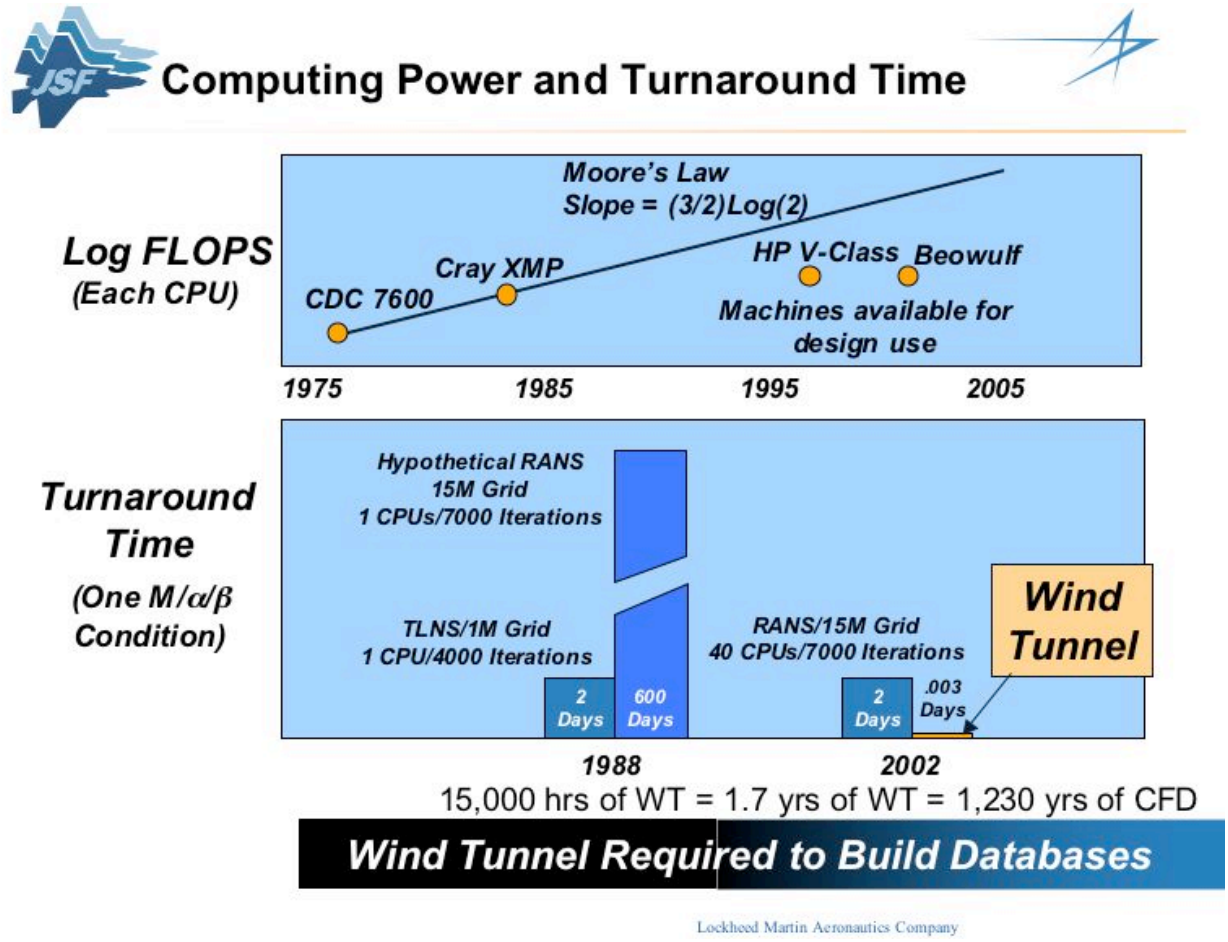
Here is the trend of computing power and turnaround time. Moore's Law illustrates the exponential growth of computing power, which is phenomenal. This has allowed much finer grids and greater number of iterations, as illustrated in lower graph. What we can do now in 2 days would have taken 600 days in 1988.

But the wind tunnel is still far faster. To do a 15,000 hour wind tunnel program takes about 1.7 years of wind tunnel time, but would take over 1200 years of CFD. So wind tunnel testing is still required for S&C databases.

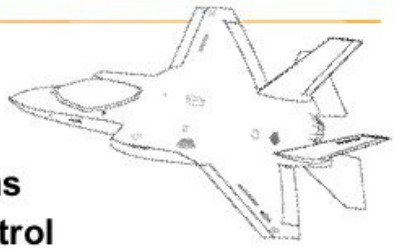


Observations

- Wind Tunnel Testing Evolved to Better Match Flight Test
  - Lessons Were Learned and Applied as Standards
- CFD has Evolved and Continues to Evolve to Better Address Specific Questions
- Application of CFD to S&C Has Been Slow Due to Complexity of S&C Areas of Interest
  - Need to Develop & Document Lessons Learned to Build on Application of CFD to S&C
- Advancing Computer Hardware Enabling Tremendous Growth in Capability
- Current and Near-Future Hardware Advancements May Enable Greater Application of CFD to S&C
- Advancements are Needed to Push Forefront of S&C Predictions (Software, Application of Theory, Experience, Lessons Learned)

CFD has great potential for helping in S&C, but we will have to work it now to make that happen.

Summary & Recommendations



- CFD Has Powerful Strengths & Applications
  - For Both Performance & Stability & Control
- Important Aero Characteristics Challenge CFD State-of-the-Art
- CFD Results Not Available in Time to Support S&C in Development
- Advancements in Computer Hardware Invite More Aggressive Application of CFD to S&C
- Tremendous Benefit Would be Realized with CFD Advancements
  - Aircraft Capability, SDD Cost & Schedule, Operating Cost, Safety

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Issues, Challenges & Payoffs: A Boeing User's Perspective on CFD for S&C

NASA COMSAC Symposium
September 23-25, 2003
NASA Langley Research Center
Hampton, Virginia

D.R. Bogue, T.R. Lines, R.D. Doll
Boeing Commercial Airplanes
Seattle, Washington

Why Hasn't S&C used CFD???

- Implementation of CFD into S&C practices has been limited by CFD capabilities, grid generation expertise, and computing availability.

- Failure to address these issues will prevent technical benefits from being realized.

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Why Hasn't S&C used CFD???

Validation
Limited (or no) validation cases has made correlations speculative for new problems

Expertise
Historically high levels required, both for geometry and for use of the codes. Adequate training requires management commitment

Grid Generation
New configurations require 1-4 weeks

Computational Limits
Let's face it, we run a lot of difficult conditions

- Process Issues must be considered, although not necessary to involve NASA

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Removing the Process Roadblocks

Boeing Commercial's philosophy is to transition technology into the hands of the end users, largely through process automation. This allows developers to concentrate on emerging technology and large scale analysis to be done by design and support groups. Items shown on page 5 are essential to adoption of CFD for the S&C culture.

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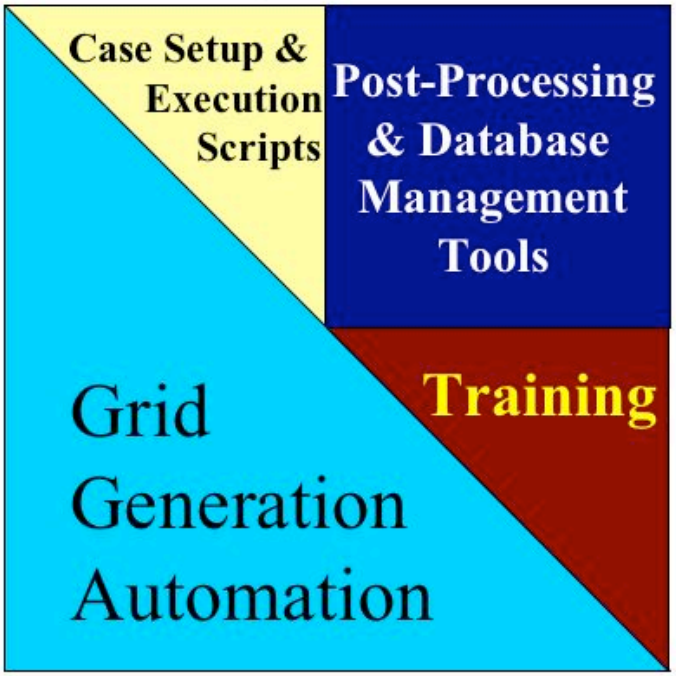
Removing the Process Roadblocks



- All Elements of the puzzle must be addressed in order to use CFD effectively

TARGET

New user able to perform a matrix of NS calculations with 1 day training in 1 week.

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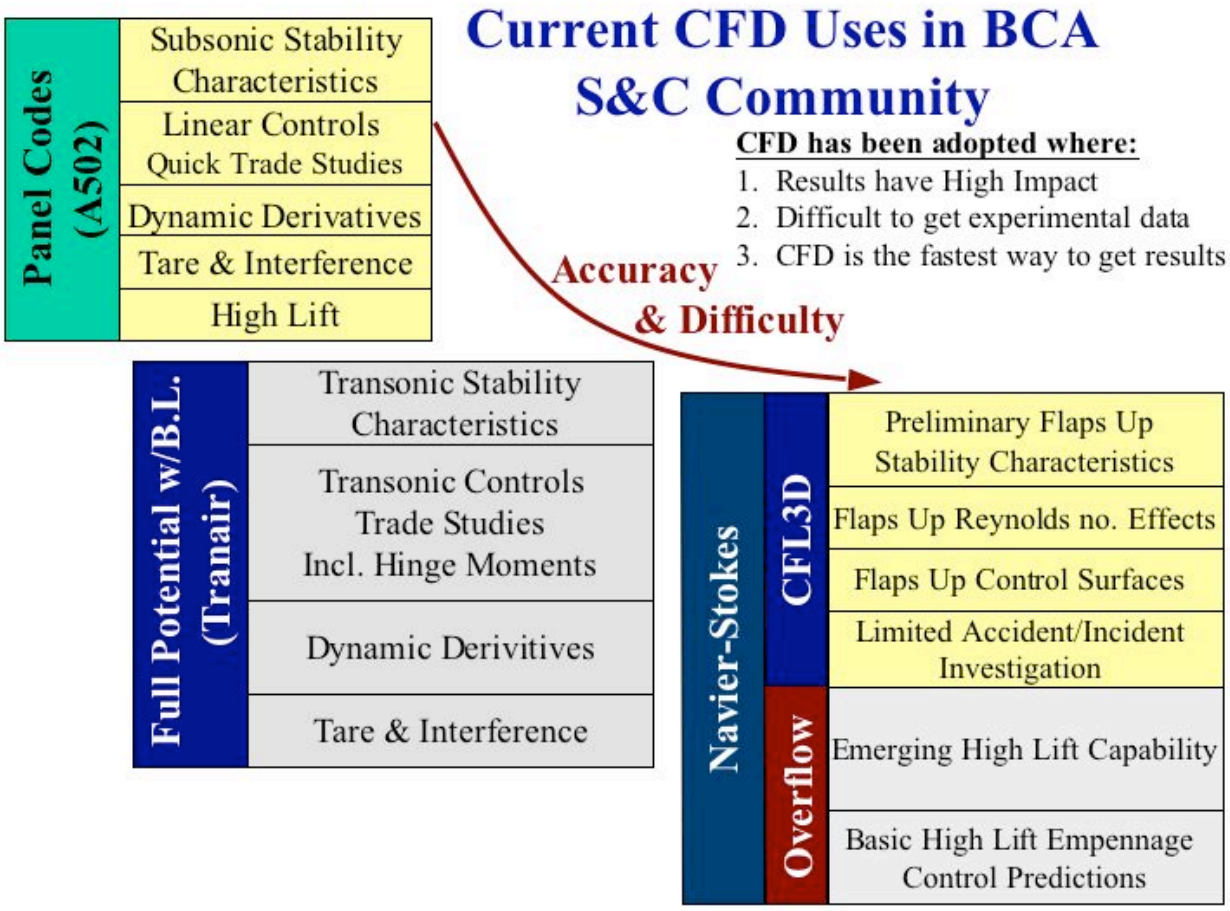
Current CFD Uses in BCA S&C Community

- BCA practice is to choose best code from a suite of CFD tools. Choice of code is guided by accuracy requirements, analysis timeline, number of cases and ease of use for suitable codes.
- Codes adopted where they buy their way on to a program. Examples:
    - Aerodynamic Center Prediction (pre-wind tunnel)
    - Reynolds number effects
    - Dynamic Derivatives
- CFD is generally complementary to wind tunnel and flight test data. Early results may be obtained prior to wind tunnel testing. Subsequent cases may be used to expand or correct wind tunnel testing results to flight levels. Post flight analyses can provide results beyond the flight envelope or for other conditions that are difficult to isolate.
- Current capabilities do not generally replace wind tunnel testing, and are not anticipated to do so for some time to come.


Current CFD Uses in BCA S&C Community
CFD has been adopted where:
1. Results have High Impact
2. Difficult to get experimental data
3. CFD is the fastest way to get results
Accuracy & Difficulty
Panel Codes (A502)
Subsonic Stability Characteristics
Linear Controls Quick Trade Studies
Dynamic Derivatives
Tare & Interference
High Lift
Full Potential w/B.L. (Tranair)
Transonic Stability Characteristics
Transonic Controls Trade Studies Incl. Hinge Moments
Dynamic Derivitives
Tare & Interference
Navier-Stokes
CFL3D
Overflow
Preliminary Flaps Up Stability Characteristics
Flaps Up Reynolds no. Effects
Flaps Up Control Surfaces
Limited Accident/Incident Investigation
Emerging High Lift Capability
Basic High Lift Empennage Control Predictions

Anticipated Uses of CFD in Stability & Control

- Technology enhancements are good.
- Items that provide better answers, easier throughput and less computational resources are better.

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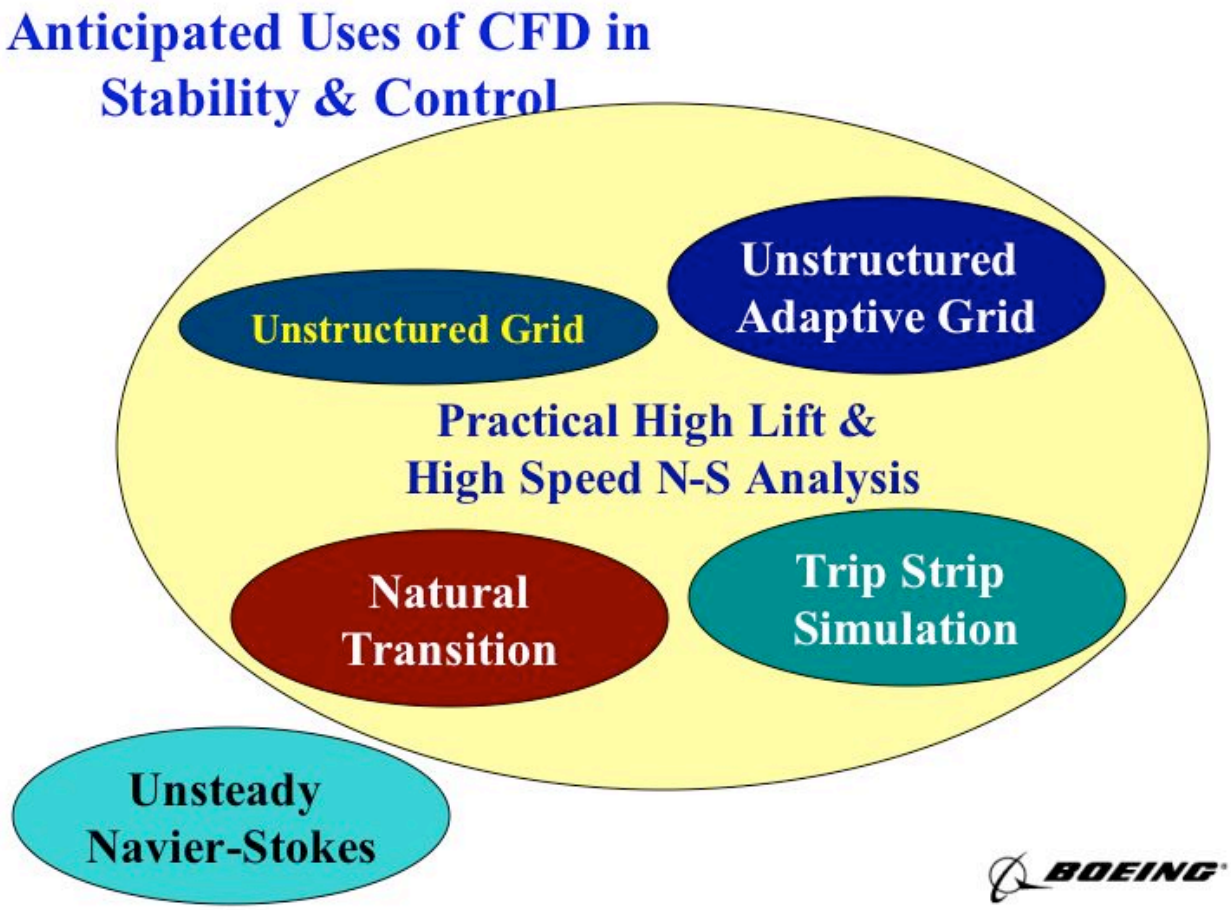
Anticipated Uses of CFD in
Stability & Control
Unstructured Grid
Unstructured
Adaptive Grid
Practical High Lift &
High Speed N-S Analysis
Natural
Transition
Trip Strip
Simulation
Unsteady
Navier-Stokes
BOEING

Some Payoffs of Using CFD

- Most of these payoffs are very difficult to quantify.
- Cycle time benefits have potentially huge leverage.

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Some Payoffs of Using CFD

Vortex Generator Development	Wind Tunnel Testing costs > 1M$
Hinge Moment Testing	Transonic Model & Testing costs between 1-10M$
Reynolds Number Testing	Elimination of Expensive Pressure Wind Tunnel Testing (Ames 11', NTF …) to get Reynolds number Effects
Cycle Time	Potentially huge impact. Timing determines value.
Risk Reduction	Inability to certify an airplane could cripple the company.
Fleet Support	Keeps the airplanes flying and customers happy.
Multi-disciplinary Collaboration	Reduced analysis and testing time. Single source of aerodynamic data. Difficult to quantify.

- *In order to have the largest payoff, CFD technology must be available to support a new airplane program.*

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Overview of Top Ten List

A series of challenge problems are posed to assess the accuracy of CFD methods for Stability & Control problems. Several of these items have already been addressed, and others are in work. The expectation to have some assessment of CFD in these areas is driven by desires to integrate CFD into the 7E7 design process with consequent deadlines.

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Overview of Top Ten List

(Actually top 11, but who's counting)

Validation/ Correlation Approach

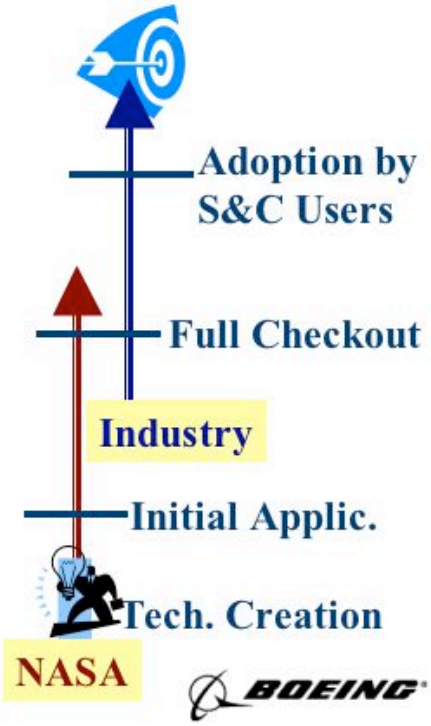
Problem Selection

- Good Database Needed
  - Atmospheric Wind Tunnel (with Pressure Data)
  - Pressure Tunnel Reynolds Effects (i.e. NTF data)
  - Flight data with full corrections
- Interesting Physics

Initial Assessment Expected in ~2 years

- Approach:
  - Attempt solutions with existing methods
  - Utilize emerging technologies as needed

Problems presented in rough prioritized order



High Speed Pitch and Sideslip Characteristics

- Past Experience: Vortex Generator Development

CFD modeling of basic characteristics including Mach, alpha and beta effects is fundamental to using CFD in other areas. High speed flight is a good place to start since the flaps are stowed, resulting in a single element airfoil.

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High Speed Pitch and Sideslip Characteristics

Task Description

- Total & Distributed Loads
- WT to Flight Scaling (incl. Trips)
- Reynolds Number & Trip Effects
- Affects Wing Design/ Selection, Vortex Generator Layout, Wing Loads and Flight Characteristics

Payoff

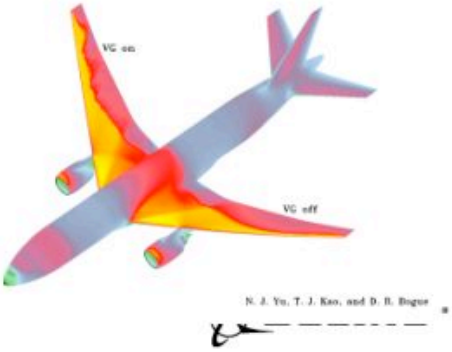
Performance: Optimum Config. Selection
Cost: Reduced W.T. & Flight Testing
Cycle Time: Single source database
Accuracy: Improved Flt. Charact. Prediction
Safety: Unusual Conditions & Configs.

Challenge Problem

Complete 777 Config. (w/VG's & w/o VG's)

- WT to Flight Scaling (incl. Trips)
- Coverage of flight envelope, including Alpha, Mach and Beta
- Tail On & Off
- 777 Development Wing – Unusual VG Effect

Computational Simulation of A Commercial Airplane Configuration with Vortex Generators



N. J. Yu, T. J. Kao, and D. R. Bogue

High Speed Lateral Controls

- Past Experience: Accident Investigation beyond flight envelope

High speed lateral control authority is a critical element to getting the wing planform right. CFD allows the S&C community to quantify the roll authority prior to wind tunnel testing including scale effects.

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High Speed Lateral Controls

Task Description

- Effectiveness/ Reversal
- Hinge Moments
- Reynolds Number Effects
- Total & Distributed Loads
- Affects Wing Design/ Selection, Vortex Generator Layout, Wing Loads and Flight Characteristics

Payoff

Performance: Optimum Config. Selection
Optimum Actuator Sizing
Cost: Reduced W. Tunnel Tests
Cycle Time: Single source database
Accuracy: Improved Flt. Charact. Prediction
Safety: Unusual Conditions & Configs.

Challenge Problem

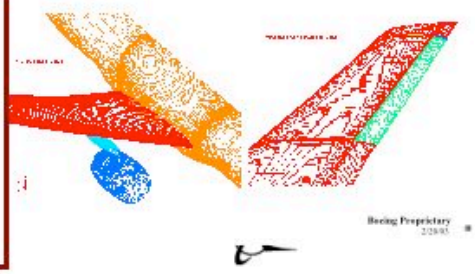
1. Analysis of 777 OB Aileron(NTF&BTWT)

- Rigid and Tested (Elastic) Shapes
- Coverage of Mach and limited alphas
- Reversal Characteristics (also for spoilers)

2. 777 OB Spoiler Reversal (BTWT)

- 4 Spoiler angles(+5,+10,+20,+45deg)
- 5 Machs at 8 angles each
- Single vs Multi-Panel Characteristics

Wing/Body & Strut/Nacelle Model



High Speed Empennage Characteristics

- Past Experience: Hail damage assessment on elevator authority

High speed empennage authority is a critical element to getting the tail planform right. CFD allows the S&C community to quantify the pitch authority prior to wind tunnel testing including scale effects.

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High Speed Empennage Characteristics

Task Description

- Stabilizer / Elevator & Rudder
- Effectiveness & Hinge Moments
- Reynolds Number Effects
- Total & Distributed Loads
- Affects Tail Planform, Control System Design, Actuator Size, Tail & Body Loads, Failure Conditions and Flight Characteristics

Payoff

Performance: Enables Optimum Tail Sizing
Optimum Actuator Sizing
Cost: Reduced W. Tunnel Tests
Cycle Time: Single source database
Accuracy: Improved Flt. Charact. Prediction
Safety: Unusual Conditions & Configs.

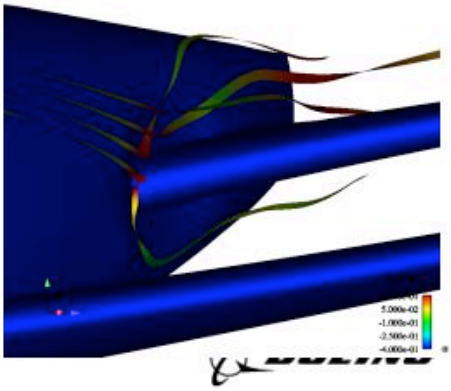
Challenge Problem

1. Analysis of 777 Stab/ Elev. (NTF&BTWT)

- WT to Flight Scaling (incl. Trip Strips)
- Stab. Angles: Off, -3,-1,+1
- Elevator Angles: -10,-5,0,+5,+10
- Tail vs Body vs Wing Effects

2. Analysis of 777 Rudder (BTWT)

- Mach and Beta Sweep
- 4 deflection angles



Flaps Down Pitch & Sideslip Characteristics

- Past Experience: Re-positioning of 727 leading edge for improved performance

CFD modeling of basic characteristics including Mach, alpha and beta effects is fundamental to using CFD in other areas. Flaps down configurations are notoriously difficult to grid, and do not appear to be mature at this point. Still since high lift problems encompass at least 50% of S&C problems, the ability to model flaps down configurations is critical towards adopting CFD for S&C.

BOEING

Flaps Down Pitch & Sideslip Characteristics

Task Description

- Leading Edge Optimization for Stall Characteristics
- Linear Range, High Alpha (incl Post-Stall), High Beta
- Reynolds Number Effects
- Total & Distributed Loads
- Operational Issues: Ice, Frost, Patches
- Affects High Lift Performance, Flight Characteristics, Tail Sizing, and Failure Conditions

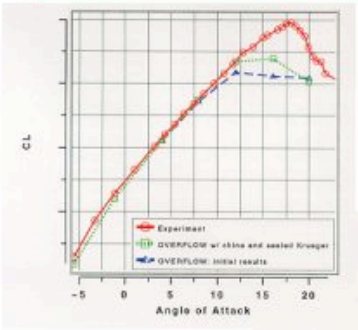
Challenge Problem

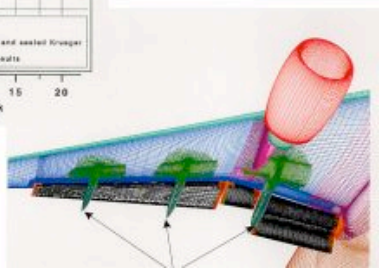
777 High Lift System (QinetiQ,NTF)

- WT to Flight Scaling
- Takeoff & Landing
- Tail on and tail off
- Autoslat Effectiveness
- Slat Skew (Failure mode) / Flap Loss
- Nacelle Chine On & Off
- Ice & Frost Effects

Payoff

Performance: Optimum Config. Selection
Cost: Reduced W.T. & Flight Testing
Cycle Time: Single source database
Accuracy: Improved Flt. Charact. Prediction
Safety: Slat Skew Prediction
Surface Imperfections





High Lift Empennage Characteristics

- Past Experience: Take-Off Rotation Control Authority

High Lift empennage authority is a critical element to getting the tail planform right. CFD allows the S&C community to quantify the pitch authority prior to wind tunnel testing including scale effects.

BOEING

Flaps Down Empennage Characteristics

Task Description

- Stabilizer/ Elevator/ Rudder Control Authority
- Reynolds Number Effects
- Total & Distributed Loads & Hinge Moments
- Total & Distributed Loads
- Operational Issues: Ice, Frost, Patches
- Affects Tail Planform, Flight Characteristics, and Failure Conditions

Challenge Problem

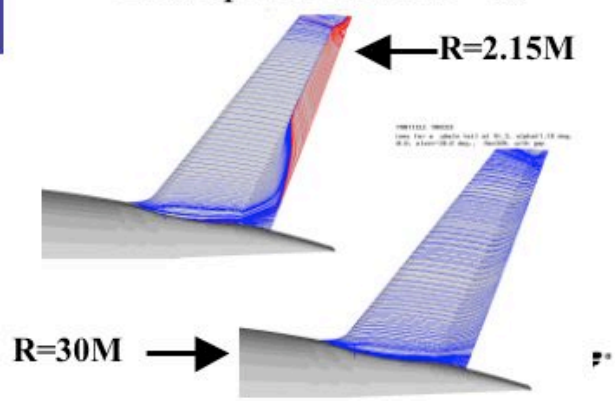
777 Empennage w/ Max Ctrls (QinetiQ)

- WT to Flight Scaling
- Landing Flap
- Stab Angles: -12,.-8,-4,0,+4
- Elevator & Rudder: -30,-20,-10,0,+10,+20
- Variation of Alpha and Beta
- Ice & Frost Effects

Payoff

Performance: Enables Optimum Tail Sizing
Optimum Actuator Sizing
Cost: Reduced W. Tunnel Testing
Cycle Time: Single source database
Accuracy: Improved Flt. Charact. Prediction
Safety: Unusual Conditions & Configs.

Low Speed Elevator –20°



High Lift Lateral Controls

- Past Experience: Roll Control Authority near Stall

High Lift lateral control authority is a critical element to getting the wing planform right. CFD allows the S&C community to quantify the roll authority prior to wind tunnel testing including scale effects. High lift problems encompass at least 50% of S&C problems, the ability to model flaps down configurations is critical towards adopting CFD for S&C.

BOEING

Flaps Down Lateral Control

Task Description

- Spoiler and Aileron Characteristics
- Reynolds Number Effects
- Total & Distributed Loads
- Hinge Moments
- Affects Wing Layout, Flight Characteristics, and Failure Conditions

Challenge Problem

777 Wing Lateral Controls (QinetiQ)

- WT to Flight Scaling
- Landing Flap
- Ailerons: +15,+10,+7.5,+5,0,-10,-20,-30
- Spoiler: 0,+2,+5,+10,+20,+45
- Variation of Alpha and Beta

Payoff

Performance: Optimum Config. Selection
Optimum Actuator Sizing
Cost: Reduced W. Tunnel Testing
Cycle Time: Single source database
Accuracy: Improved Flt. Charact. Prediction
Safety: Unusual Conditions & Configs.

BOEING

Wind Tunnel Tare & Interference and Wall Simulation

- Impact: Shocks observed reflecting off ceiling at high Mach numbers

Wind Tunnel Tare & Interference and Wall Simulation

- Past Experience: High lift effects on trap wing experiment

Testing on the trap wing at high lift conditions has shown that wall corrections with CFD were necessary to get the T&I effects right. Additionally, shock reflections off the ceiling have been observed at high Mach numbers.

BOEING

Wind Tunnel Tare & Interference and Wall Simulation

Task Description

- Better Correlation of Wind Tunnel to Flight
- High and Low Speed Simulation needed (BTWT & QinetiQ mounts)
- Total & Distributed Loads
- Longitudinal and in Sideslip
- Affects Flight Characteristics, and Aircraft Loads.

Challenge Problem

1. High Speed (BTWT & ARC 11')

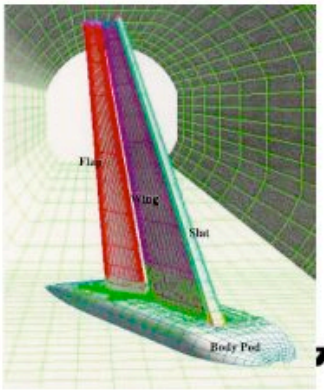
- Lower Swept Strut, USS & Plate
- Variation of Mach, Alpha & Beta

2. High Lift (QinetiQ)

- Standard Boeing Mount (UWAL style)
- Variation of Mach, Alpha & Beta
- Reynolds number Effects

Payoff

Performance: N/A
Cost: Reduces/ Eliminates T&I Testing
Cycle Time: Reduces W.T. Testing
Accuracy: Known problems areas:
* CLmax. Sideslip, High Mach
Note: Necessary for High Mach CFD validation. May be necessary for High Lift.



Dynamic Derivative Evaluation

- Past Experience: Negative roll damping at stall.

Dynamic derivative prediction affects the tail size and requirements for a yaw damper. These characteristics are nearly impossible to obtain experimentally.

BOEING

Dynamic Derivative Evaluation

Task Description

- High Speed (Flaps Up)
- Low Speed (Landing Flaps)
- Longitudinal and Lateral/Directional
- Rotary and Lag Derivatives
- Rate Effect of Control Surfaces
- Total and Distributed Loads
- Affects Flight Charact., Systems Layout.

Payoff

Performance: Optimum tail sizing
Improved Control System
Cost: Decision to install yaw damper
Cycle Time: Single source database
Accuracy: Improved Flt. Characteristics
Understand of Rate Effects
Safety: Unusual Conditions & Configs.

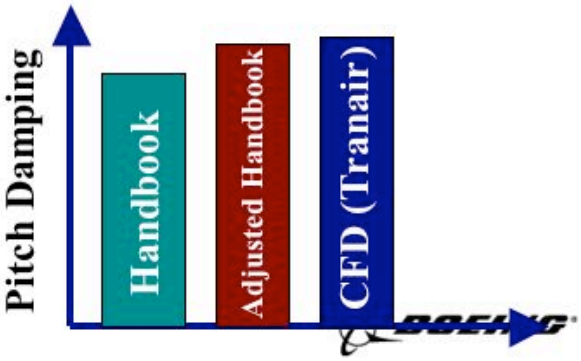
Challenge Problem

1. 777-200 Flaps Up (Flight)

- Mach Sweep through M.97
- Frequency Variation (all axes)

2. 777-200 Flaps Down (Flight)

- Negative Roll Damping at Stall
- Dutch Roll Prediction
- Rate of Control Surfaces
- Frequency Variation (all axes)



Ground & Thrust Effects

- Past Experience: Take-Off Rotation

Ground and thrust effects are both difficult to determine experimentally. Ground plane testing does not allow significant changes to the ground height, and thrust testing is a series of compromises.

BOEING

Ground & Thrust Effects

Task Description

- High Lift Condition (Flaps Down)
- Ground Plane Variation
- Thrust Level Variation (alone & combined)
- Variations in Tunnels are limited & expensive
- Affects Flight Characteristics, and Aircraft Loads.

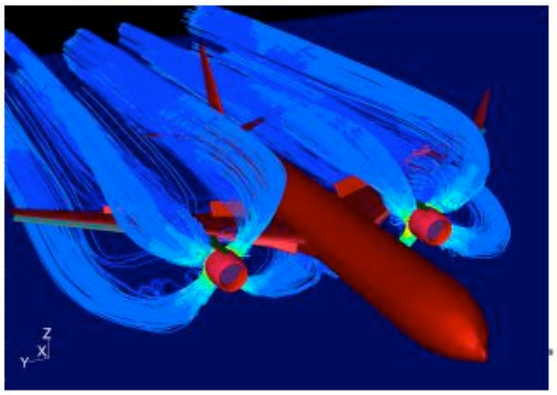
Payoff

Performance: N/A
Cost: Reduced W.Tunnel & Flight Testing
Cycle Time: Single source database
Accuracy: Improved Flt. Charact. Prediction
Understand of Rate Effects
Safety: Taxi, Thrust Reverser

Challenge Problem

777-200 Flaps Down (Flight)

- Evaluation at various heights
- Symmetric & Asymmetric Thrust effects
- Ground and Thrust Effects together.
- Extreme Sideslip (up to 90deg) (incl. Thrust)
- Rate of Control Surfaces
- Thrust Reverser Simulation (Ground Effect)



Streamlined Processes

- Streamlined processes are a critical element to adoption of CFD by the S&C culture.

BOEING

Streamlined Processes

Task Description

- Streamlined Processes
- Pre-processing and Execution
- Post-Processing and Data Mining
- Affects: Practical use of end product

Payoff

Performance: N/A
Cost: Manpower to use analysis
Cycle Time: Big Effect
Accuracy: Consistent Process
Training: Reduced expertise

Challenge Problem

1. 777 High Speed (Flaps Up)
- 2 Configs, 50 cases (wbsnhv)
- 2 weeks

2. 777 High Lift (Flaps Down)
- 5 configurations, 8 alphas each
- 2 weeks

BOEING

Integrated Structural Modeling

- Aeroelastics play a significant role in nearly every S&C characteristic. The ability to model aeroelastic effects, especially in the non-linear range, will help match experimental data sources.

BOEING

Integrated Structural Modeling

Task Description

- Structural Integration
- Affects: Aeroelastics, W.Tunnel Interpretation

Payoff

Performance: N/A
Cost: ??
Cycle Time: Single source database
Accuracy: Improved Flt. Characteristics

Challenge Problem

????

BOEING

Stability and Control in Computational Simulations for Conceptual and Preliminary Design

the past, today, and future?

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whmason@vt.edu

Computational Methods for Stability and Control Symposium
Hampton, VA
September 23-25, 2003

The Problem In Conceptual Design

This attitude is only slightly exaggerated, and both sides have good reasons for their attitudes. In essence, it appears to originate because detailed control system development, and the assessment of aircraft characteristics in terms of stability and control, requires an understanding of the aerodynamic characteristics at flight boundaries. Here, nonlinear aerodynamics typically produced a significant flow separation and component interactions dominate the analysis.

The Problem In Conceptual Design

The Flight Controls Guys
(if they're even there, and worse, they may be EEs):

"We need a complete 6 DOF, with an aero math model from -90° to + 90° or else forget it"

The Conceptual Designers:

"Just Use the Usual Tail Volume Coefficient"

Exaggerated? —Not That Much!

"Linear" aero finds the close connection between performance and dC_m/dC_L: the X-29

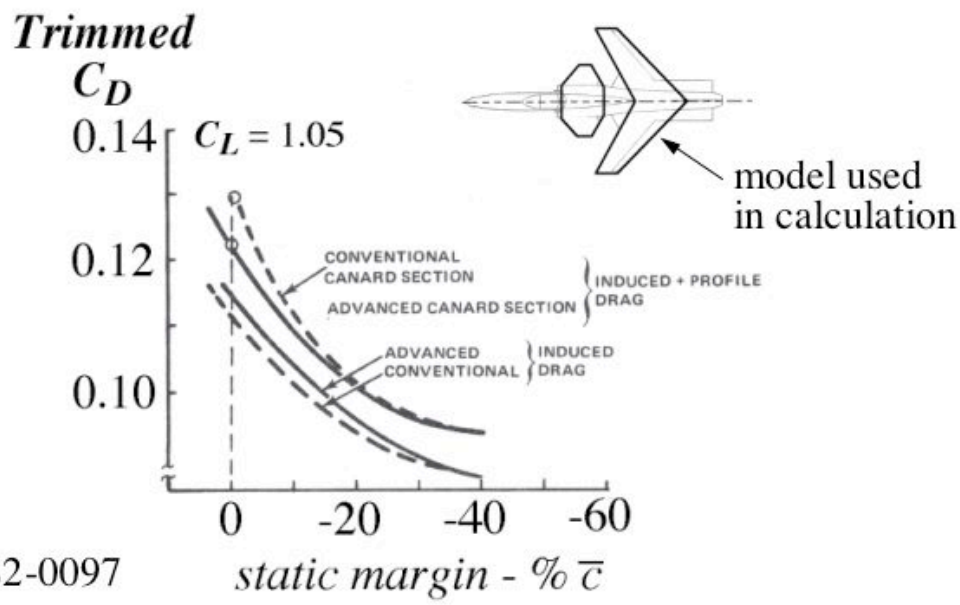
The initial computational work in stability and control came about in the mid-60s, when numerous methods to predict lift and pitching moment slopes were developed. For the early stages of design the vortex lattice method emerged as the standard, and the Margason/Lamar code was used widely. Designers were mainly interested in predicting the neutral point of the basic configuration.

With the introduction of fly-by-wire and relaxed static stability concepts to increase vehicle performance, stability and control needed to become an essential part of the early design process. This was done when longitudinal stability was connected to the trimmed drag of the airplane to determine the center of gravity location (and the related static margin) required to achieve maximum performance. John Lamar converted his code to compute minimum trimmed drag, allowing the static margin for minimum trimmed drag to be found early in the design process. An example that illustrates this type of stability vs. performance layout process in the extreme is the X-29. After including transonic airfoil drag empirically in Lamar's induced drag code, it was found that to achieve the performance potential of the Grumman forward swept wing concept, the configuration had to be about 35% unstable.

This example is from W.H. Mason, "Wing-Canard Aerodynamics at Transonic Speeds - Fundamental Considerations on Minimum Drag Spanloads," AIAA Paper 82-0097, January 1982

"Linear" aero finds the close connection between performance and dC_m/dC_L: the X-29

- Performance was strongly related to design static stability



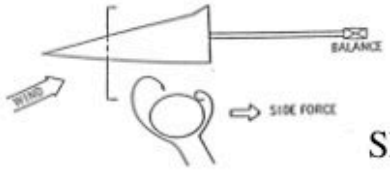
AIAA 82-0097

Nonlinear CFD study captures the F-5 directional stability from the forebody

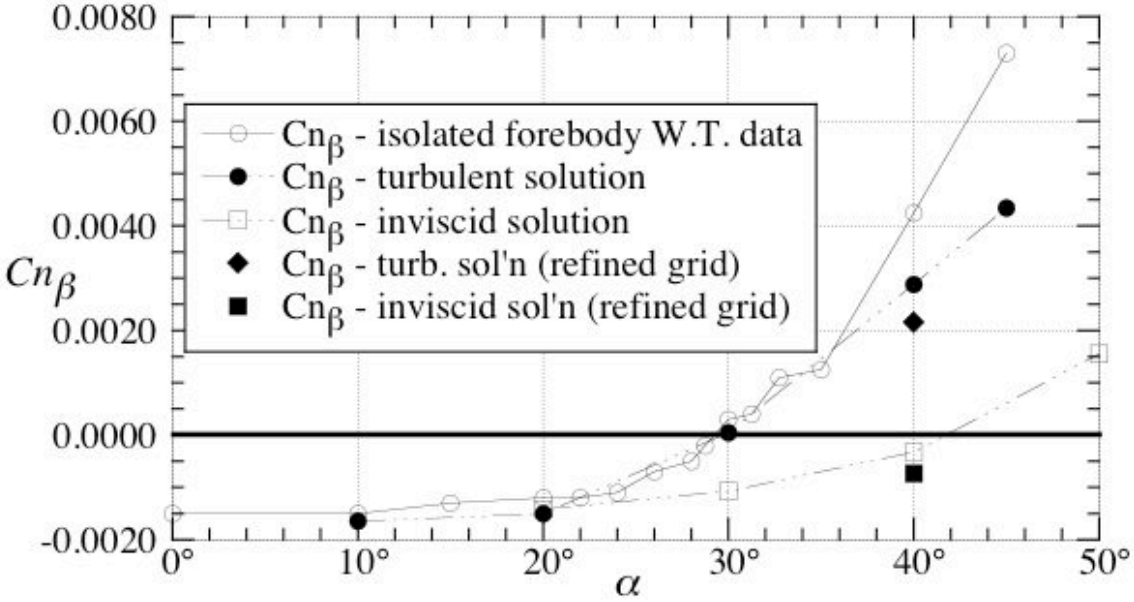
Joe Chambers, Sue Grafton and Paul Coe discovered that the forebody of the F-5 controlled the directional stability of the entire aircraft at high angles of attack. The sketch shows the tunnel test setup and their flow hypothesis. The plot shows the wind tunnel data and the results of a CFD computation. We were able to come reasonably close to reproducing the wind tunnel test computationally. The next chart illustrates the origin of the integrated force.

W.H. Mason and R. Ravi, "Computational Study of the F-5A Forebody Emphasizing Directional Stability," *Journal of Aircraft*, Vol. 31, No. 3, May-June 1994, pp. 488-494.

Nonlinear CFD study captures the F-5 directional stability from the forebody



Sketch from NASA TN D-7716, 1974



Journal of Aircraft, Vol. 31, No. 3 May-June 1994, pp. 488-494.

CFD also allows designers to understand the physics so they can be designed

The CFD results can be used to understand the origin of the directional stability characteristics of the F-5A forebody. Comparing inviscid and viscous results, the role of viscosity can be explicitly identified. We also see that it the integrated force is the result of a rather complicated balance of forces. The associated computational flow visualization, available in the references below, also provide insight into the structure of the flowfield.

We also did similar calculations for chine-shaped forebodies. The references cited below provide the details.

W.H. Mason and R. Ravi, "Computational Study of the F-5A Forebody Emphasizing Directional Stability," *Journal of Aircraft*, Vol. 31, No. 3, May-June 1994, pp. 488-494.

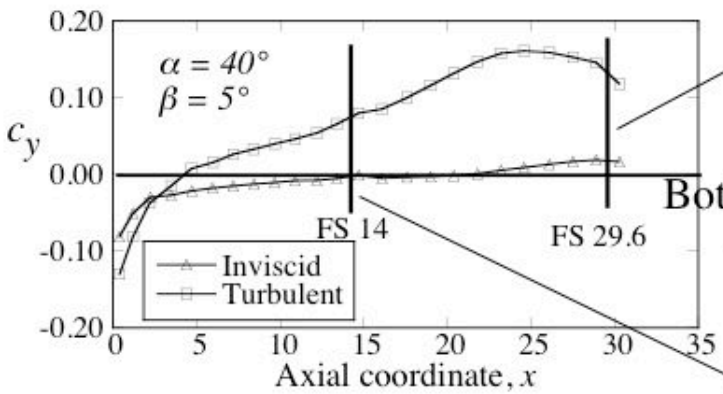
Ravi and W.H. Mason, "A Computational Examination of Directional Stability for Smooth and Chined Forebodies at High-α," NASA CR 4465, August 1992.

R. Ravi and W.H. Mason, "Chine-Shaped Forebody Effects on Directional Stability at High-α," *Journal of Aircraft*, Vol. 31, No. 3, May-June 1994, pp. 480-487.

CFD also allows designers to understand the physics so they can be designed

F-5A Forebody: CFL3D solution

NASA CR 4465, 1992



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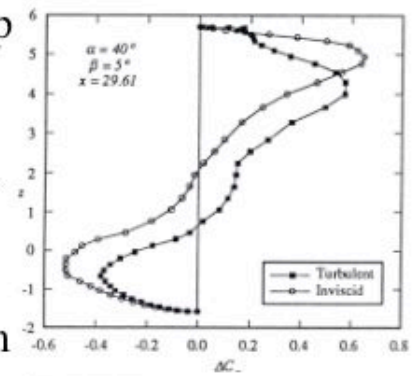

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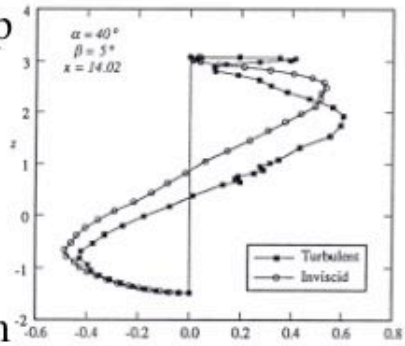


Bottom

ΔCp

- shaping can tailor characteristics
- chine forebodies also investigated
- next: add yaw damping

One example illustrating the incorporation of a key stability and control characteristic - pitchup - in an MDO design process

The key to incorporating nonlinear aerodynamics in design is the use of models to represent the nonlinear aerodynamics without directly incorporating the expensive aerodynamic simulations. At Virginia Tech we've been doing this with response surface models. These are typically quadratic polynomials, and Crisafulli used four response surfaces to represent the pitchup characteristics of cranked wings. Our approach amounts to the development of a "data base" of solutions for a particular design project. This approach is effective in exploiting the capabilities of parallel computing.

Alex Benoliel and W.H. Mason, "Pitch-Up Characteristics for HSCT Class Planforms: Survey and Estimation," AIAA Paper 94-1819, June 20-23, 1994.

Crisafulli, P., Kaufman, M., Giunta, A.A., Mason, W.H, Grossman, B., Watson, L.T, and Haftka, R.T, "Response Surface Approximations for Pitching Moment, Including Pitch-Up, in the MDO Design of an HSCT," AIAA Paper 96-4136, Sept. 1996.

Mason, W.H., Knill, D.L., Giunta, A.A., Grossman, B., Haftka, R.T. and Watson, L.T., "Getting the Full Benefits of CFD in Conceptual Design," AIAA 16th Applied Aerodynamics Conference, Albuquerque, NM, AIAA Paper 98-2513, June 1998.

See also:

Giunta, A.A., Golovidov, O., Knill, D.L., Grossman, B., Mason, W.H., Watson, L.T., and Haftka, R.T., "Multidisciplinary Design Optimization of Advanced Aircraft Configurations," *Fifteenth International Conference on Numerical Methods in Fluid Dynamics,* P. Kutler, J. Flores, J.-J. Chattot, Eds., in Lecture Notes in Physics, Vol. 490, Springer-Verlag, Berlin, 1997, pp. 14-34.

One example illustrating the incorporation of a key stability and control characteristic - pitchup - in an MDO design process

Approach

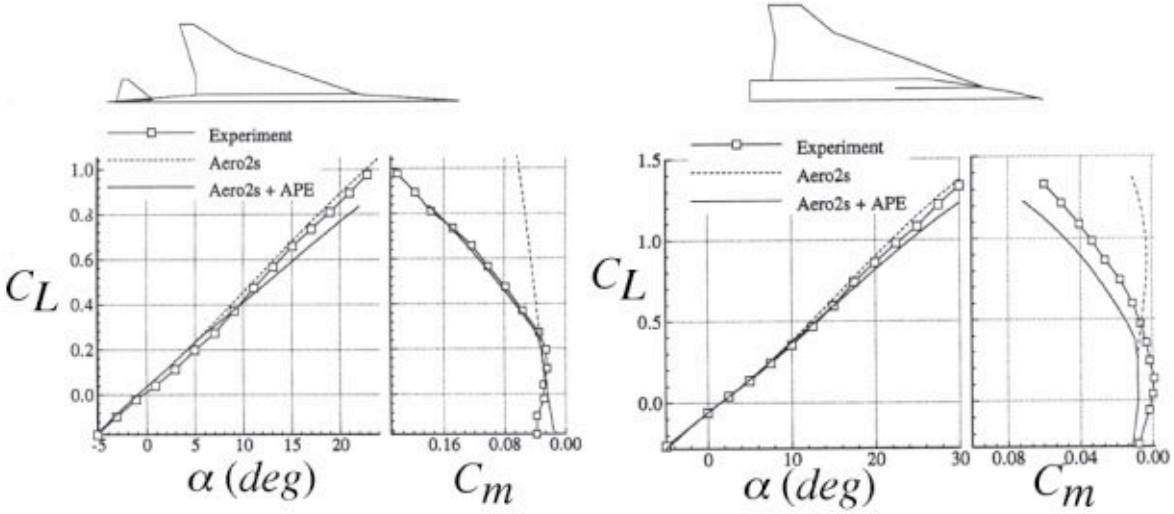
- develop a means of estimating pitchup for cranked wing planforms of interest for supersonic aircraft (HSCT) (Benoliel and Mason, AIAA Paper 94-1819)
- represent the nonlinear aero characteristics with a model that can be "called" many thousands of times during the MDO optimization process.
  (Crisafulli, et al, AIAA Paper 96-4136)
- an overview of this approach has been presented in a form suitable for aerodynamicists in AIAA 98-2513.

The analysis model

Alex Benoliel and W.H. Mason, "Pitch-Up Characteristics for HSCT Class Planforms: Survey and Estimation," AIAA Paper 94-1819, June 20-23, 1994.

The analysis model

For cranked wings, a model illustrating the effect of the limiting lift that could be carried on the outboard wing of an HSCT-type planform was developed:



APE: Aerodynamic Pitchup Estimation

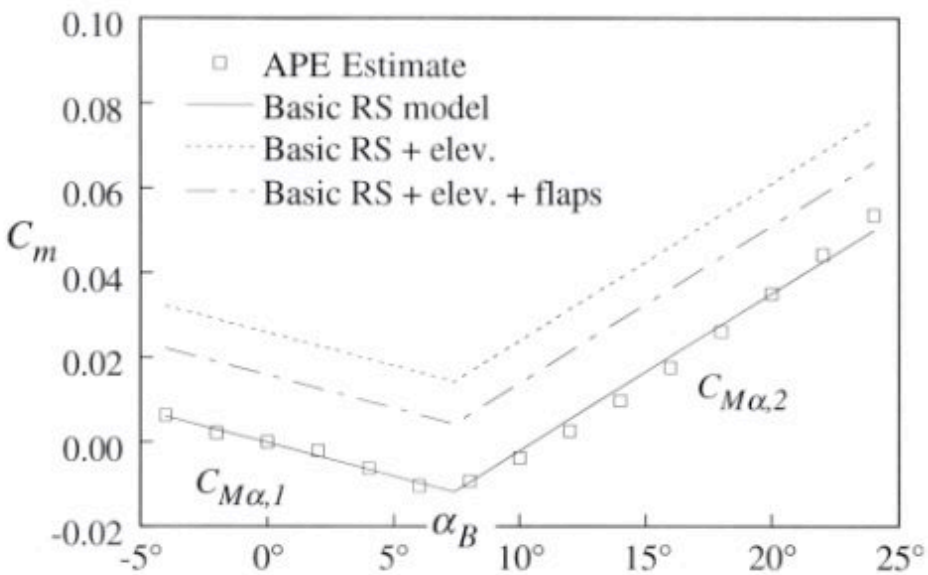
AIAA Paper 94-1819

Application to Design

Crisafulli, P., Kaufman, M., Giunta, A.A., Mason, W.H, Grossman, B., Watson, L.T, and Haftka, R.T, "Response Surface Approximations for Pitching Moment, Including Pitch-Up, in the MDO Design of an HSCT," AIAA Paper 96-4136, Sept. 1996.

Application to Design

- model the nonlinear aero with 2 straight lines and and α_B
- develop a "data base" (DOE) for this model in terms of the planform variables, a *Response Surface*, RS



AIAA 96-4126

MDO Results: An HSCT study

With the model of the pitchup characteristics established, the design can be done using MDO methods. In this case, many other control constraints are also included.

Crisafulli, P., Kaufman, M., Giunta, A.A., Mason, W.H, Grossman, B., Watson, L.T, and Haftka, R.T, "Response Surface Approximations for Pitching Moment, Including Pitch-Up, in the MDO Design of an HSCT," AIAA Paper 96-4136, Sept. 1996.

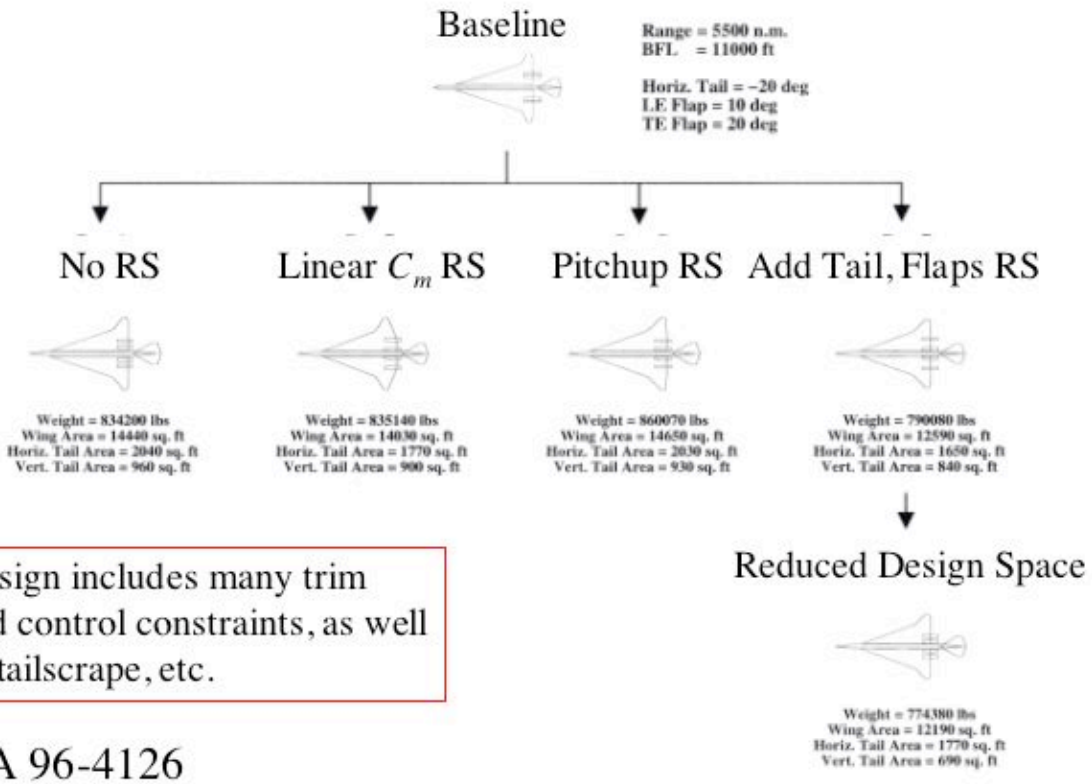
The final development of this methodology was described in the paper by Pete MacMillin, et al:

P.E. MacMillin, J. Dudley, W.H. Mason, B. Grossman, and R.T. Haftka, "Trim, Control and Landing Gear Effects in Variable-Complexity HSCT Design," AIAA Paper 94-4381, Panama City, Fl., September 1994.

MacMillin, P. E., Golividov, O., Mason, W.H. Grossman, B., and Haftka, R.T., "Trim, Control, and Performance Effects in Variable-Complexity High-Speed Civil Transport Design," MAD Center Report 96-07-01, July 1996. Virginia Tech, Blacksburg, VA

MacMillin, P. E., Golividov, O., Mason, W.H. Grossman, B., and Haftka, R.T., "An MDO Investigation of the Impact on Practical Constraints on an HSCT Configuration," AIAA Paper 97-0098, Reno, NV, January 1997.

MDO Results: An HSCT study



Design includes many trim and control constraints, as well as tailscrape, etc.

AIAA 96-4126

Stability and Control in Tail Sizing: RSS/Active Controls

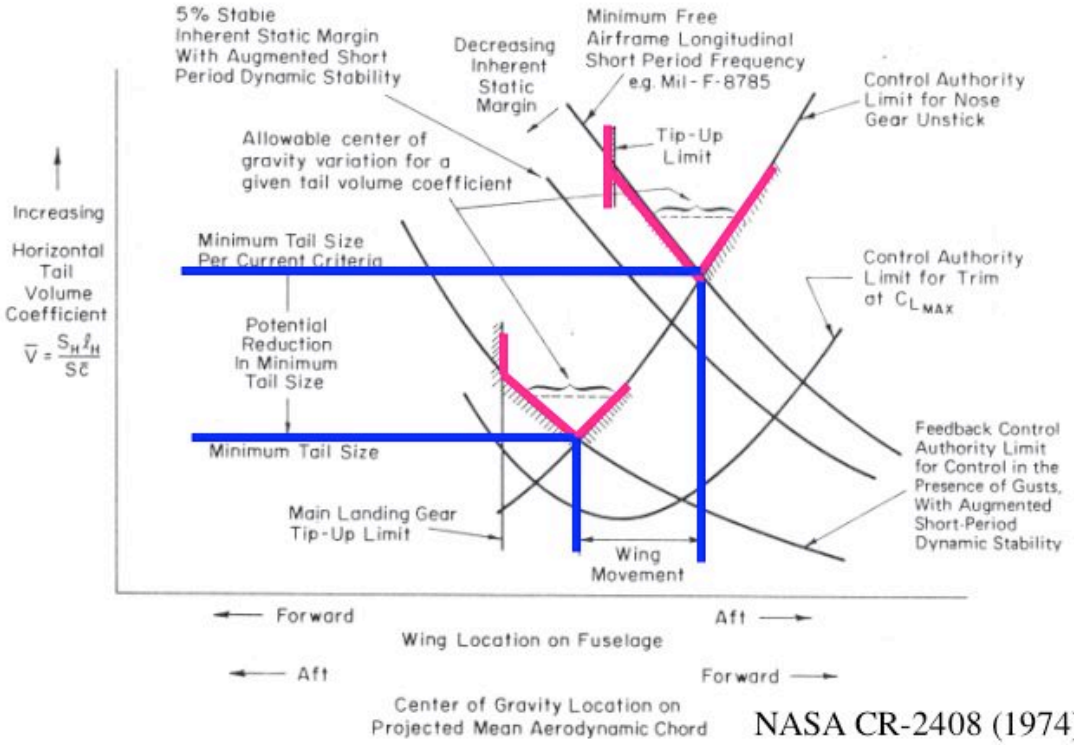
The connection between stability and control and conceptual aircraft design has been of special interest since active control started being considered. Many attempts to get active controls into the early stages of design have been made. This chart comes from a report arising from a panel discussion in the early 1970s.

L. Gregor Hofmann and Warren F. Clement, "Vehicle Design Considerations for Active Control Application to Subsonic Transport Aircraft," NASA CR-2408, August 1974.

Another example of how this could be done is available in:

Anderson, M. R. and Mason, W.H., "An MDO Approach to Control-Configured-Vehicle Design," AIAA Paper 96-4058, Sept. 1996.

Stability and Control in Tail Sizing: RSS/Active Controls



NASA CR-2408 (1974)

Conceptual/Preliminary Design Tools

- Linear Aerodynamics
  - Static stability characteristics
  - Control effectiveness
  - Dynamic stability characteristics
- Nonlinear Aerodynamics
  - Flow separation effects
  - Forebody/wing/canard vortex interactions
- Propulsion-related controls
  - and active flow control
- Accuracy expectations

Example of "Scorecard" Validation: the XB-70

Of course, "calibrated" estimates of control effectiveness should be made for the aerodynamic predictions, although there is considerable uncertainty. Our experience is that it is hard to generalize for all configurations. One good example came from McDonnell Douglas in St. Louis:

Thomas, R.W., "Analysis of Aircraft Stability and Control Design Methods," AFWAL-TR-84-3038, Vol. II, App. B., "Evaluation of Aerodynamic Panel Methods," by John Koegler, May, 1984.

At this point, the progress of stability and control computations in conceptual and preliminary slowed down. However, the linear methods continue to be key to design, and are continually being assessed. One example is the "Pie Charts" used to assess the capability of APAS, DATCOM and VLM methods for the XB-70.

Valery Razgonyaev and W.H. Mason, "An Evaluation of Aerodynamic Prediction Methods Applied to the XB-70 for Use in High Speed Aircraft Stability and Control System Design," AIAA Paper 95-0759, 33rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 12, 1995.

And the methods have formed the basis for a rudimentary system that can be used by students, and has been adopted elsewhere:

J. Kay, W.H. Mason, F. Lutze and W. Durham, "Control Authority Issues in Aircraft Conceptual Design," AIAA Paper 93-3968, August 1993.

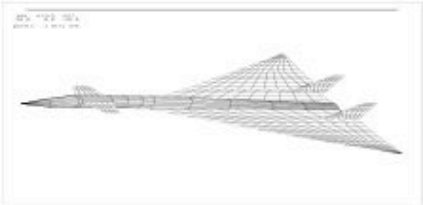
Jacob Kay, W.H. Mason, W. Durham, F. Lutze and A. Benoliel, "Control Power Issues in Conceptual Design: Critical Conditions, Estimation Methodology, Spreadsheet Assessment, Trim and Bibliography," VPI-Aero-200, November 1993. http://www.aoe.vt.edu/~mason/Mason_f/MRsoft.html#ControlPower

Dynamic stability derivative predictions from Digital DATCOM were by Blake:

W.B. Blake, "Prediction of Fighter Aircraft Dynamic Derivatives Using Digital Datcom," AIAA Paper 85-4070, Colorado Springs, CO, October 1985.

Example of "Scorecard" Validation: the XB-70

AIAA 95-0759



Stability derivatives

Derivative	$C_{L\alpha}$	$C_{m\alpha}$	C_{mq}	$C_{Y\beta}$	$C_{n\beta}$	$C_{l\beta}$	C_{lp}	C_{nr}
Subsonic	◕	◕	◕	○	◕	◕	○	◕
Supersonic	○	◑	◑	○	○	●	◕	◑

Control derivatives

Derivative	$C_{L\delta f}$	$C_{m\delta f}$	$C_{n\delta f}$	$C_{l\delta f}$	$C_{L\delta c}$	$C_{m\delta c}$	$C_{Y\delta r}$	$C_{n\delta r}$	$C_{l\delta r}$
Subsonic	○	◕	◑	◕			◕	◕	◑
Supersonic	◕	◕	◕	●	○	○	○	○	◑

It's hard to generalize results in code validation and verification

Very good	Good	Fair	Poor	Not useful
Error<10%	10%<Error<25%	25%<Error<50%	50%<Error<100%	100%<Error
○	◕	◑	◕	●

Note: Marty Waszak asked us for this

Needs

- Geometric Flexibility
- Rapid Analysis
- Various fidelity analyses
- Software designed for MDO
- Validation/Risk reduction

An aside: design requires

- the *cg* range, inertias
- aeroelastic effects on stability and control characteristics, e.g., Bhatia, AIAA 93-1478

CFD Challenge Problems

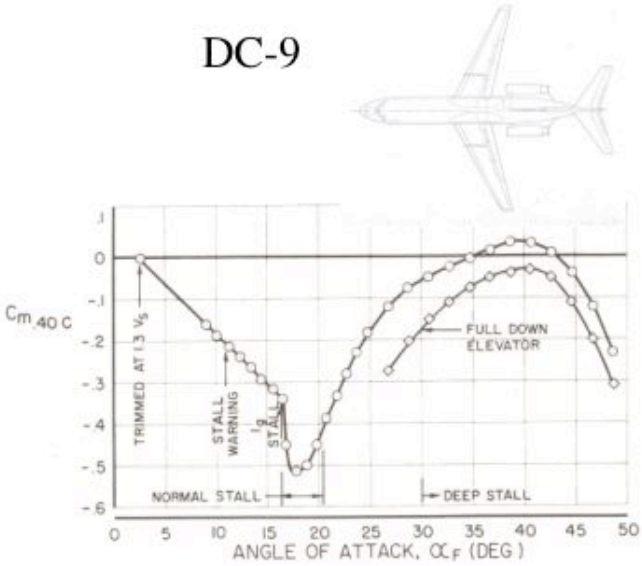
These famous pitchup and deep stall cases, one for a T-tail transport aircraft and one for a fighter with strakes, illustrate critical characteristics that need to be understood early in the design phase. They also illustrate the complexity of the challenge. The critical conditions are associated with separated flows with a combination of flow features and issues concerning Reynolds number effects. I have not seen any CFD calculations reproducing these wind tunnel cases. This needs to be done.

F-16 pitching moment: Nguyen, L.T., Ogburn, M.E., Gilbert, W.P., Kibler, K.S., Brown, P.W., and Deal, P.L., "Simulator Study of Stall/Post-Stall Characteristics of a Fighter Airplane With Relaxed Longitudinal Static Stability," NASA TP 1538, Dec. 1979).

DC-9 pitching moment: Shevell, R.S., and Schaufele, R.D., "Aerodynamic Design Features of the DC-9," *Journal of Aircraft*, Vol. 3, No. 6, Nov.-Dec. 1966, pp. 515-523.

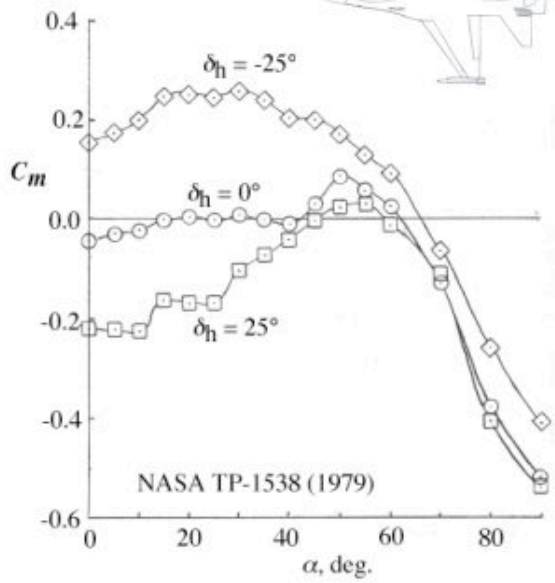
CFD Challenge Problems

DC-9



Shevell and Schaufele,
Journal of Aircraft, Vol. 3, No. 6,
pp. 515-523 (1966)

F-16



Advanced concepts are "non-standard" leading to new computational challenges

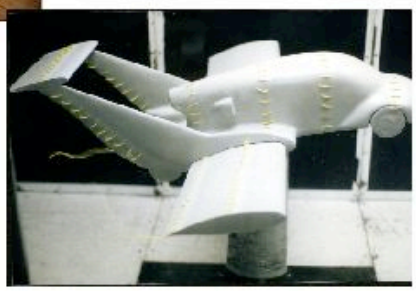
The concepts here include a strut braced wing on an A-7, as proposed for REVCON a few years ago, and which required special transonic analysis of the wing-pylon-strut junction (Andy Ko, W.H. Mason and B. Grossman, "Transonic Aerodynamics of a Wing/Pylon/Strut Juncture," 21st AIAA Applied Aerodynamics Conference, Orlando, FL, AIAA Paper 2003-4062, 23-26 June 2003)

Another concept is Leroy Spearman's "Inboard Wing" concept, which requires modeling the "tip vortex" when the wing has fuselage "end plates"

We also see Jones' oblique wing, Askin Isikveren's X-wing, Joe Schetz's quasi ring wing, and a Jim Marchman design team's roadable aircraft. Each of these concepts present different challenges, and we haven't even included any morphing concepts.

Advanced concepts are "non-standard" leading to new computational challenges

Today's concepts come in a staggering array of shapes, all presenting unusual aero modeling requirements, now including UAVs and morphing

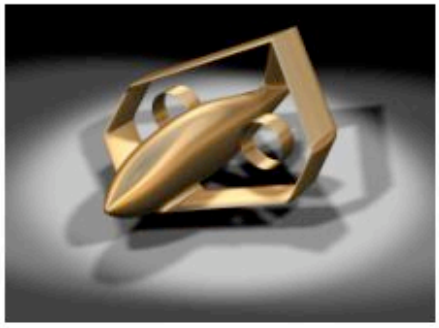


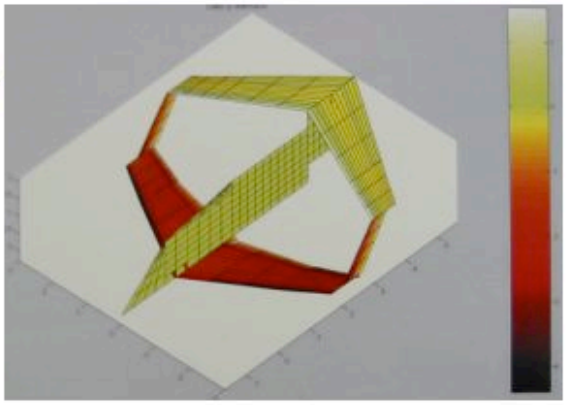
Competition: Europe has an organized effort

It's worth mentioning that the Europeans have a coordinated effort that covers a broad range of CFD applications in aircraft design. The overview in Progress in Aerospace Sciences cited here provides some insight into this program.

Competition: Europe has an organized effort

- Vos, Rizzi, Darracq and Hirschel, "Navier-Stokes solvers in European aircraft design," *Progress in Aerospace Sciences*, Vol. 38, 2002
  - ***An eye-opening example of a well-conceived, effective program***
- The best subsonic linear tool? *Tornado*, from KTH (Sweden)





A truly arbitrary geometry VLM code, in MATLAB, and available free off the web. Simple enough for students to use in design

Potential Approaches

The sensitivity approaches are particularly interesting, although Bob Hall has pointed out that they won't pickup hysteresis effects.

Limache, A C; Cliff, E M, "Aerodynamic sensitivity theory for rotary stability derivatives," Atmospheric and Flight Mechanics Conference, Portland, OR, Aug. 9-11, 1999, AIAA Paper 99-4313, *Journal of Aircraft* (0021-8669), vol. 37, no. 4, July-Aug. 2000, p. 676-683

Godfrey, Andrew G; Cliff, Eugene M, "Direct calculation of aerodynamic force derivatives - A sensitivity-equation approach," Aerospace Sciences Meeting & Exhibit, 36th, Reno, NV, Jan. 12-15, 1998, AIAA Paper 98-0393

Michael A. Park, Lawrence L. Green, Raymond C. Montgomery, David L. Raney, "Determination of Stability and Control Derivatives Using Computational Fluid Dynamics and Automatic Differentiation," AIAA Paper 99-3136

Potential Approaches

- Geometric generality
  - asymmetric configurations
  - ground effects, multiple planes
  - "morphing" concepts, including nonconventional controls
- Aerodynamic fidelity
  - fast linear theory
  - approximate aerodynamic theories of the past still relevant
    - *insight for design from variable groupings, limiting behavior - not available from CFD*
  - high fidelity codes/mesh generation with results fast enough for use on design problems (create RS models)
  - static and dynamic stability derivatives from sensitivity analysis (Cliff et al, AIAA Papers 98-0393, 99-4313, Park, *et al*, AIAA Paper 99-3136)
- Integrated aero-propulsion flowfield methodology for control (including active control)

To Conclude

- Aerodynamic stability and control characteristics will be more and more important to future designs
- A coordinated effort to develop a suite of tools/understanding is critical for US competitiveness in advanced flight vehicle design

Note: Most of the papers described are available electronically at:
http://www.aoe.vt.edu/people/whmason.html

My name is Lawrence Green. I work in the NASA Langley Multidisciplinary Optimization Branch. There, I sit both literally and figuratively between the high-fidelity CFD gurus and the S&C practitioners here at NASA Langley. The talk title is now somewhat different than was published in your program, but now reflects the intended focus of the talk. I'd like to thank my co-authors, Angela Spence and Patrick Murphy for their help, and the conference organizers for allowing me to speak today.

Computational Methods for Dynamic S&C Derivatives

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Computational Methods for Stability and Control (COMSAC) Symposium, September 23-25, 2003

This is an outline of my presentation. First, I'll give some S&C background and then describe some CFD background. I'll state my research objectives for the past year. I'll then describe several CFD methods and results for static, steady rate, and dynamic S&C derivatives. Finally, I'll summarize and draw some conclusions from the work.

Outline

- S&C Background
- CFD Background
- CFD Research Objectives
- CFD Methods and Results
- Summary / Conclusions

Aircraft designers, flight control designers, and the flight dynamics community in general must account for the variation of forces and moments under maneuvering conditions. Maneuvering F&M can be largely different than static F&M and may exhibit nonlinear unsteady behaviors. To help designers a large knowledge base has been developed using S&C parameters to characterize aircraft dynamics. Dynamic stability parameters (derivatives), in particular, provide information about the "stiffness" and "damping" of the dynamic system. This discussion will focus on issues associated with how the "damping" derivatives, that characterize F&M variation with respect to angular rates, are modeled and measured.

Aircraft equations of motion (EOM) begin with Newton's 2nd Law. Application of this law requires an inertial reference frame but for convenience the equations are translated to the rotating aircraft body-axis system. This produces the nonlinear inertial terms shown above.

S&C Background
Aircraft EOM

- Aircraft designs must account for changing forces & moments during maneuvers
- S&C parameters (derivatives) reflect changes to forces & moments
- One key set of parameters are dynamic stability derivatives
- Aircraft is a nonlinear dynamical system
  - EOM with appropriate assumptions:
  - Translation $m\dot{\vec{V}} + \vec{\omega}\times m\vec{V} = \vec{F}_{aero} + \vec{F}_{prop} + \vec{F}_{gravity}$
  - Rotation $I\dot{\vec{\omega}} + \vec{\omega}\times I\vec{\omega} = \vec{M}_{aero}$
  - Kinematics $\dot{\vec{\Theta}} = L\,\vec{\omega}$

Equations for translation, rotation, and kinematic relationships produce a system of nonlinear ordinary differential equations. These equations are written with several other assumptions to make the discussion more tractable: 1) Earth is inertial reference frame with no curvature; 2) Airplane is rigid with lateral symmetry; 3) Thrust acts along fuselage and through c.g.; 4) Still atmosphere, i.e., no winds or gusts; 5) Constant mass with no internal mass movements, constant inertia; 6) Body axis system is fixed to aircraft.

The Faero & Maero terms are the aerodynamic forces and moments acting on the aircraft and these must be defined in order to solve the system of ODEs. This step is where S&C issues for modeling and measuring the "damping" derivatives occur. Defining the aerodynamic model is a substantial step and a key area where CFD can make significant contributions to solving S&C problems.

To see how dynamic stability derivatives can arise, the conventional aero model for pitching moment is shown. The conventional approach to defining the aero F&M is to assume that these functions can be expanded in a linear series with constant coefficients. Nonlinear, high-order, frequency-dependent, or time-dependent terms are assumed to be zero. Additional simplifying assumptions that can be applied as appropriate are: 1) the aircraft is a rigid-body (no aero-elastic responses in structure or controls); 2) no sharp discontinuities in aero; and 3) no stochastic processes.

S&C Background
Conventional Aerodynamic Model

- Assume aero F&M can be expanded in series
  - Linear, constant coefficient equations
  - No high-order, nonlinear, time-dependent, frequency-dependent terms
- Rigid body
- No sharp discontinuities in aerodynamics
- No stochastic aerodynamic processes
- Conventional aerodynamic model
  - Series coefficients are the "stability & control" derivatives
  - e.g., pitching moment:

$$C_m(t) = C_{m_o} + C_{m_\alpha}\alpha + C_{m_q}\frac{qc}{2V} + C_{m_{\dot{\alpha}}}\frac{\dot{\alpha}c}{2V} + C_{m_{\delta e}}\delta e$$

dynamic derivatives

As an example under these assumptions, the non-dimensional pitching moment equation can be written as shown. The key S&C parameters for this discussion are the two derivatives with respect to pitch rate and angle-of-attack rate. These two angular rates can be quite different in flight.

A conventional technique, used for many years to estimate damping derivatives such as Cmq, is to perform 1-dof, planar, forced-oscillation (FO) tests. For this test the model is placed at various angles of attack in a wind tunnel and allowed to undergo forced sinusoidal oscillations at different frequencies and usually relatively small amplitudes. Oscillations are usually done about pitch, roll, and yaw axes. This method of testing produces the so-called "in-phase" and "out-of-phase" derivatives usually designated by a bar over the derivative (see equation). These coefficients are basically the Fourier coefficients obtained from harmonic analysis of the FO measurements.

S&C Background

Testing Methods for Dynamic Derivatives

- Conventional Methods
  - Forced Oscillation (1 dof planar rotations)
  - Free Oscillation (free-to-roll rig)
  - Rotary balance
- Advanced Methods
  - Combined or arbitrary motions
  - Wide-band input forced oscillations
  - Oscillatory coning
- Techniques no longer available
  - Curved-flow
  - Rolling-flow
  - Snaking technique
  - 1 dof linear translation motion (plunging, swaying, …)

A long history of S&C testing has produced many methods of testing to obtain various stability and control derivatives, however, the FO test is the primary method and virtually the only

method generally available today. Past decisions made under the general belief that other test methods were not needed lead to very few facilities in the world today having advanced capabilities or previously available capabilities such as plunging to obtain angle of attack rate derivatives, directly.

Historically, the conventional aerodynamic model has been used very successfully for developing aircraft and for predicting flight responses in certain parts of the flight envelope. However, nonlinear or unsteady behaviors can be observed in different flight regimes such as during transonic maneuvering, rapid maneuvers, or at high angle of attack. Flight predictions can quickly deteriorate at higher angles of attack and for cases where the assumptions previously stated are not satisfied. Also results can be very configuration dependent.

The first problem S&C engineers must address is that wind tunnel measurements do not support the conventional model assumption of constant coefficients and in particular constant damping

S&C Background

Limitations of Conventional Approach

- Conventional aerodynamic model – works well but has limits
  - Problem regimes: rapid maneuvers, high AOA, transonic flight
  - Constant derivative model in contradiction to experimental data
  - Issue for both military and commercial aircraft
- Conventional experiments - limited information
  - Rotary-balance testing
    - **Constant rate, steady flow measurements**
  - Single dof tests: forced-oscillation or free-to-roll
    - **Single frequency, planar motion**
    - **Combined stability derivatives**

$$\bar{C}_{L\alpha}(\alpha,k), \bar{C}_{Lq}(\alpha,k)$$

- Conventional model & conventional experiments => ad-hoc solutions for simulation/prediction, modeling, and design

Two S&C Problems:

Modeling & Measurement of dynamic stability derivatives

derivatives. This is shown by the large frequency dependence of the in-phase and out-of-phase derivatives at high angles of attack. The second problem is that the conventional FO test technique for measuring damping produces a combination of derivatives rather than separate values, as required by the series expansion of the aero F&M in the conventional model. This occurs because the angle-of-attack rate and pitch rate are kinematically constrained to be equal in single dof FO testing. Both of these problems can be ameliorated with the use of CFD.

Impacts of poor models for design are clear, especially increased research, development, and certification costs. Most of the flows of interest to the S&C community involve nonlinear, unsteady, and/or separated flows.

S&C Background
Impact of Poor Modeling

- Major impacts on aircraft programs during late development stages:
  - Delayed schedules
  - High visibility
  - Problem-solving while in flight test status
  - Cut & try solutions
  - **Increased cost**
- Many problems not identified until operationally deployed
- S&C Problems characterized by
  - Nonlinear
  - Unsteady
  - Separated flows

CFD brings unique capabilities to the S&C table. The code user can choose from a variety of code and grid fidelities to solve their problems. Many codes offer the capabilities to simulate both conventional and advanced dynamic testing techniques, as well as augmenting and enhancing current testing techniques. In addition, several derivative extraction techniques can be brought to bear on the problems including the traditional method of finite differences, symbolic manipulation, and complex mathematics. I've chosen to use a technique called automatic differentiation, which was developed by mathematicians. The technique can provide both f

CFD Background

- Capabilities complimentary to conventional S&C method
  - Wide variety of code / grid fidelities
  - Simulate conventional and advanced dynamic testing techniques
  - Augment / enhance wind tunnel testing capabilities
- Derivative techniques
  - Vary in speed, RAM and disk requirements, accuracy, and user effort
  - Finite differences ([FD] conceptually easy, but step size dependent)
  - Symbolic manipulation (e.g., Mathematica, limited scope)
  - Complex differentiation (more accurate, but similar in cost to FD)
  - Automatic Differentiation
    - **Forward (direct) and reverse (adjoint) modes**
    - **Applicable to conventional S&C and morphing vehicles**
    - **A variety of tools for various languages**
    - **ADIFOR Automatic Differentiation for Fortran**
      - **Developed by Rice University and Argonne National Labs**
      - **Exact derivatives from legacy codes via chain rule**

forward and reverse modes, applicable to both conventional S&C needs and those of morphing vehicles. There are a variety of tools available. I've used the ADIFOR tool, developed by Rice University and Argonne National Labs, to extract exact derivatives from legacy FORTRAN codes via repeated application of the chain rule.

Some previous work in which this technique was used include the application of ADIFOR to the TLNS3D code in order to extract longitudinal derivatives with respect to Mach, alpha, Reynolds number, and geometric parameters. Later, as the technical monitor for a GWU Master's student, we again applied ADIFOR to both the PMARC and CFL3D codes for the explicit purpose of computing static and steady rate S&C derivatives. With the PMARC code, we also performed a control placement effectiveness study for a morphing vehicle. In the CFL3D code, a steady state solution method for steady rate derivatives was implemented to improve the computational speed significantly over true time dependent calculations. I have also been involved in the

CFD Background

- Apply ADIFOR to TLNS3D code (transport wing in viscous, transonic flow; obtain C_D, C_L, and C_m derivatives with respect to:
  - **M, α, and Re (*Comp. Sys. in Eng.*, Vol. 3, No. 6, pp. 625-637, 1992)**
  - **Geometric parameters (AIAA 94-2197, AIAA 94-4261)**
- ICE tailless fighter vehicle (vortical and bursting flow conditions)
  - PMARC low-order panel method code (AIAA 99 – 3136)
    - **Static (α and β) and steady rate (p, q, and r) S&C derivatives**
    - **Control placement effectiveness study for morphing vehicle**
  - CFL3D Euler / Navier-Stokes code (AIAA 2000 - 4321)
    - **Static (α and β) S&C derivatives**
    - **Steady state solution for steady rate (p, q, and r) S&C derivatives**
- Advanced CFD techniques applicable to S&C
  - Efficient 2nd derivatives (AIAA 94-4262 and AIAA 2001-2529)
  - Uncertainty propagation (AIAA 2001-2528 and AIAA 2002-3140)
  - Uncertainty (confidence) bounding of S&C derivatives

3/26/04 14:41 Lawrence L. Green

development of techniques for the efficient calculation of 2nd derivatives and uncertainty propagation which allow me to place uncertainty bounds on my computed forces and moments and their associated S&C derivatives.

The previous work demonstrated the potential for using CFD to compute S&C derivatives but only scratched the surface of what could be done. As a result of the previous work I have continued to advocate for NASA to apply CFD to S&C problems. An area that I have personally advocated for the inclusion within COMSAC is the investigation of various code fidelities ranging from digital DATCOM to DES, to assess and quantify the accuracy and computational resource requirements of the various code fidelities. My branch intends to develop semi-automated means to identify and use the right code and grid fidelities code for a given application, based upon user requirements. I have an interest in bringing bounded S&C analyses into the early design process. I also returned to this area of research to extend, develop, and demonstrate CFD methods for dynamic S&C derivatives within forced oscillation and pure

CFD Research Objectives

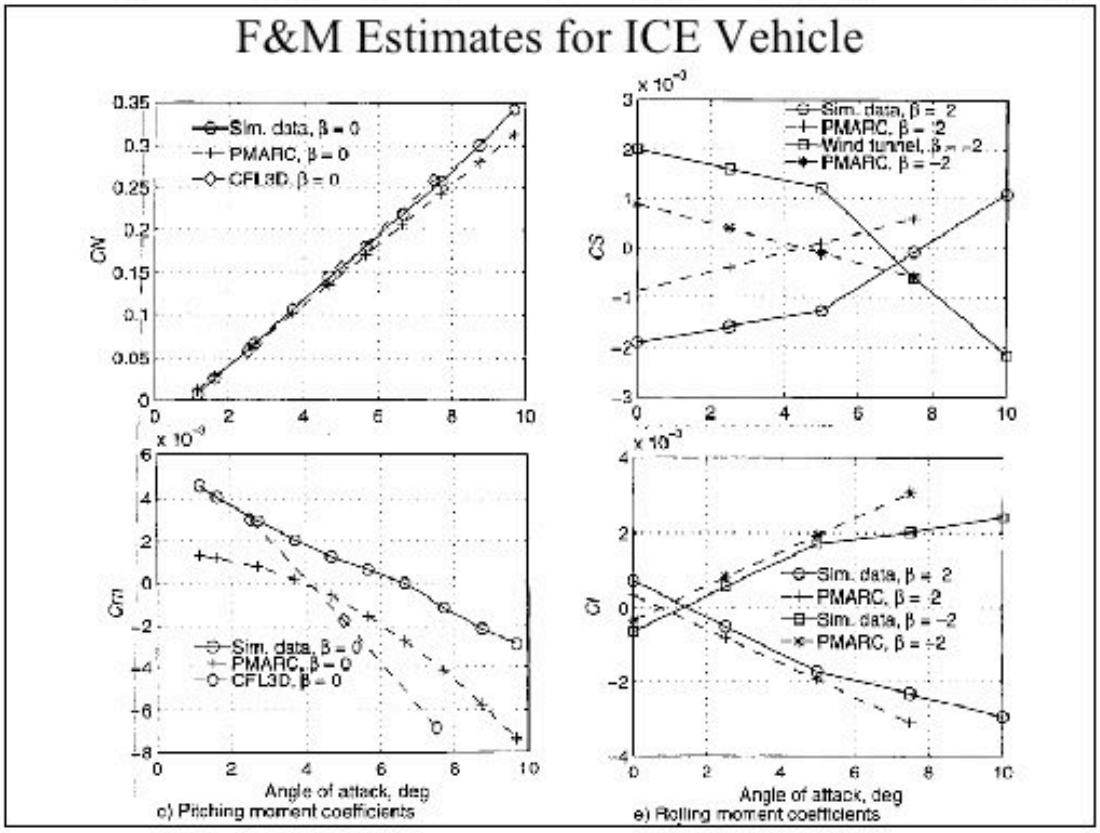
- Continue advocacy for CFD applied to S&C
- Investigation of CFD code fidelities (DATCOM to DES)
  - Assess / quantify the accuracy of code fidelities (confidence bounds)
  - Assess / quantify the resource requirements of various code fidelities
  - Identify the right fidelity code for a given vehicle/flight regime
- Bring bounded S&C analyses into early design process
- Demonstrate CFD methods for dynamic S&C derivatives
  - Extend static and steady rate methods to dynamic S&C derivatives
  - Forced oscillation and pure rotary motions
  - Separation techniques for "lumped" dynamic S&C derivatives

rotary motions. I was also interested in demonstrating the computational separation of lumped dynamic S&C derivatives, which was proposed in our 1999 paper, but never developed or demonstrated.

This plot shows several examples of computed forces and moments from both the PMARC and CFL3D codes. The upper left had figure shows CN as a function of angle of attack in degrees. The upper lright figure shows CS, the lower left figure shows Cm, and the lower right figure shows the rolling moment, Cl. The solid line with circles is the measured data, the dashed lines with pluses are the PMARC data, the dashed lines with diamonds are the CFL3D Euler data. Convergence problems were encountered with the Euler solutions, leading us to begin to compute Navier-Stokes solutions, as shown in the next figure.

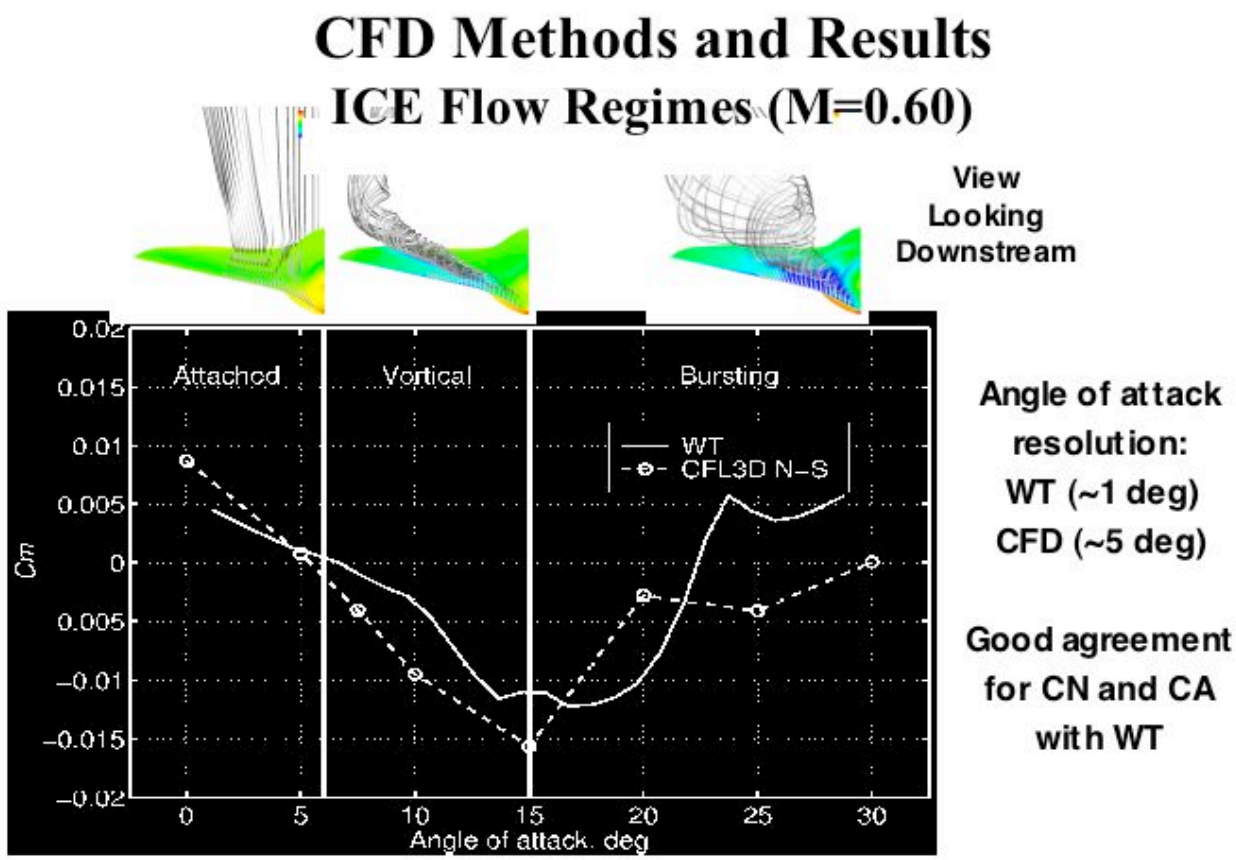
CFD Methods and Results

ADIFOR Results for ICE Vehicle (M=0.60)



This figure shows the Navier Stokes computations for Cm as a function of angle of attack. Three flow regimes were observed: attached flow up to about 6 degrees alpha, vortical flow up to about 15 degrees alpha, and vortically bursting flows beyond 15 degrees alpha. Wind tunnel measurements were taken at 1 degree increments, whereas the computations were performed only at 5 degree increments, which unfortunately, misses some key features of the measured data. The comparisons for CN and CA were in good agreement across the angle of attack range.

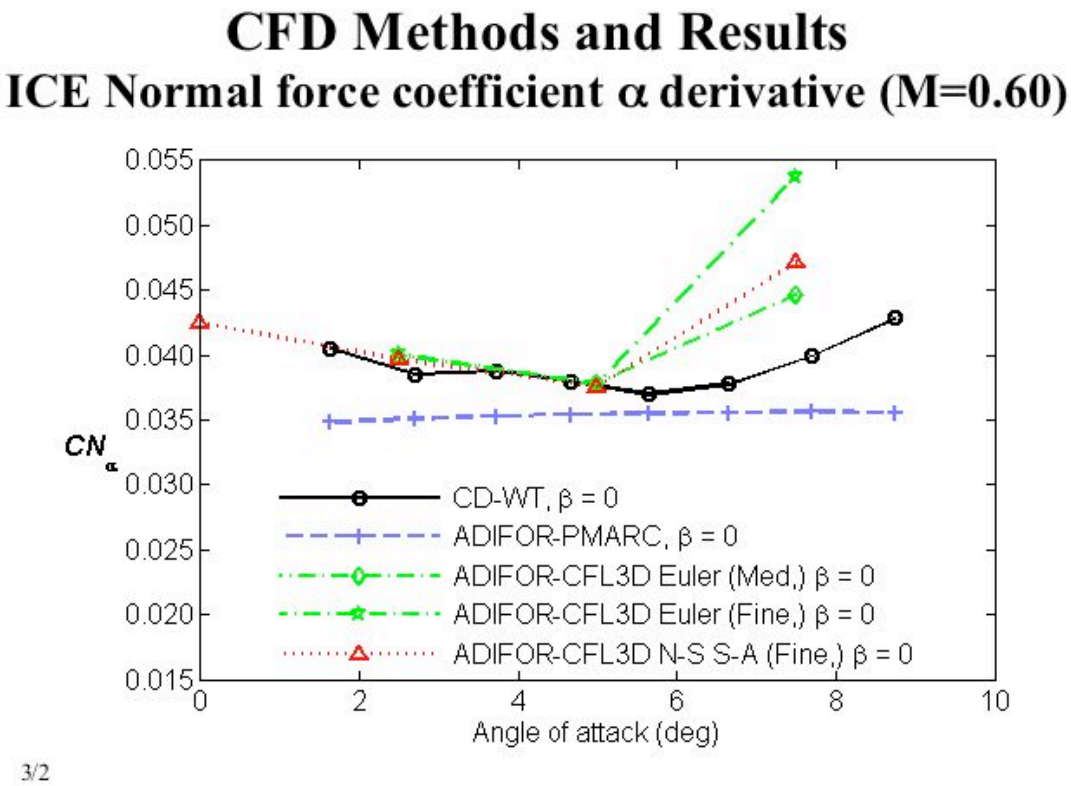
As in the picture on the ASCOT slide at the start of this talk, looking downstream, the vehicle surface is **colored with contours** of the pressure coefficient. Vortical flow structures are shown



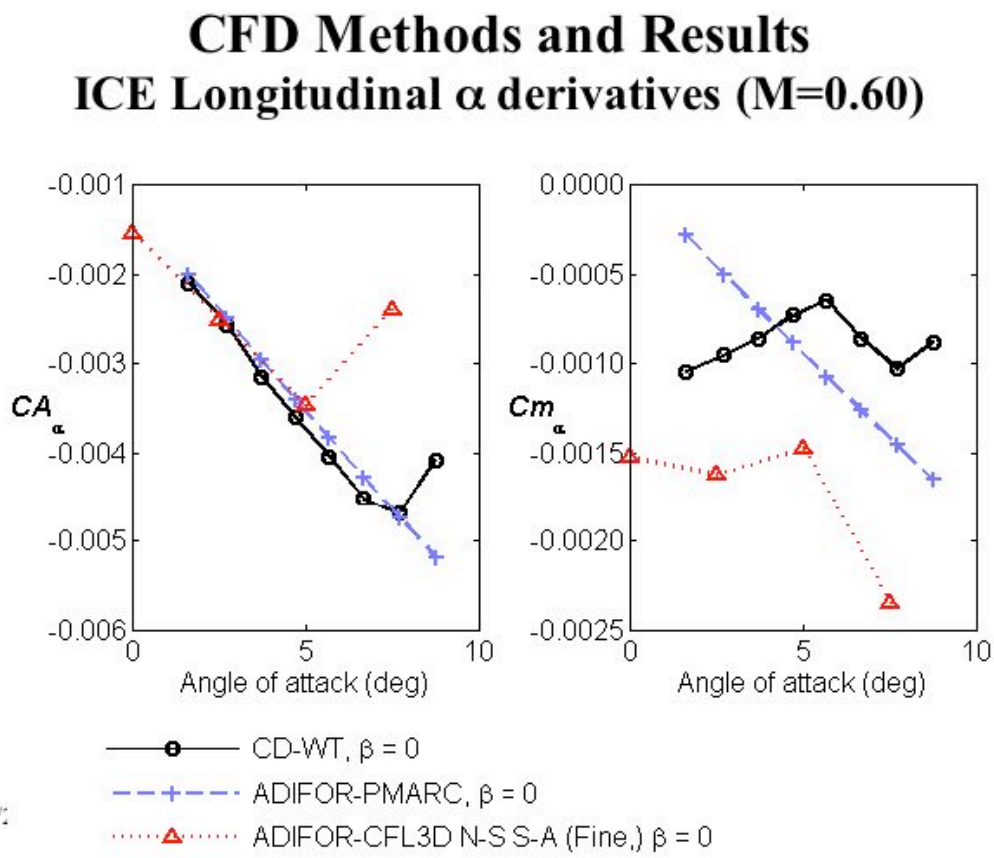
over the wing upper surface. The comparisons of CN and CA with WT were deemed to be excellent or good and are not shown.

It should be noted that there were some unexplained effects observed in the raw wind tunnel data which suggest that the model may have been slightly mis-aligned and geometrically unsymmetric upon installation.

This is the same plot with the inclusion of ADIFOR-CFL3D calculations. The two green dash-dot lines are the Euler mode of ADIFOR-CFL3D. The diamonds are the medium grid and the stars are the fine grid. The fine grid viscous ADIFOR-CLF3D Spalart turbulence model results are shown with red dotted lines and triangles. You will note that at 7.5 deg alpha the fine grid Euler converged to a significantly different value that the medium grid. The grids are not converging in a second order fashion as the grids are sequenced. It is therefore believed that different flow physics are being modeled in the two grids. Because of this reservation, the Euler results will be removed for clarity from the plots of the other two longitudinal derivatives.

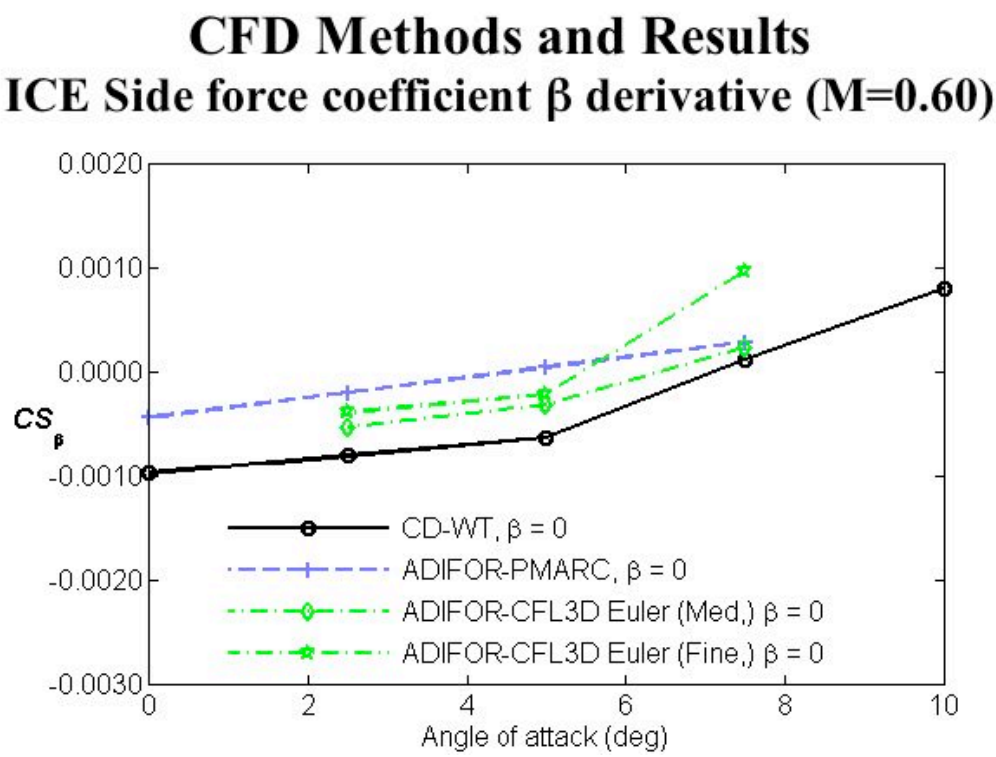


The left graph depicts the derivative of axial force coefficient with respect to angle of attack on the vertical axis. The right graph depicts the derivative of pitching moment coefficient with respect to angle of attack on the vertical axis. The turbulent Navier-Stokes solution had difficulty matching the pitching moment derivative exactly, but did show a similar shape to the data. Pitching moment is one of the more difficult quantities to predict with CFD, therefore, a derivative of pitching moment would be even more challenging.

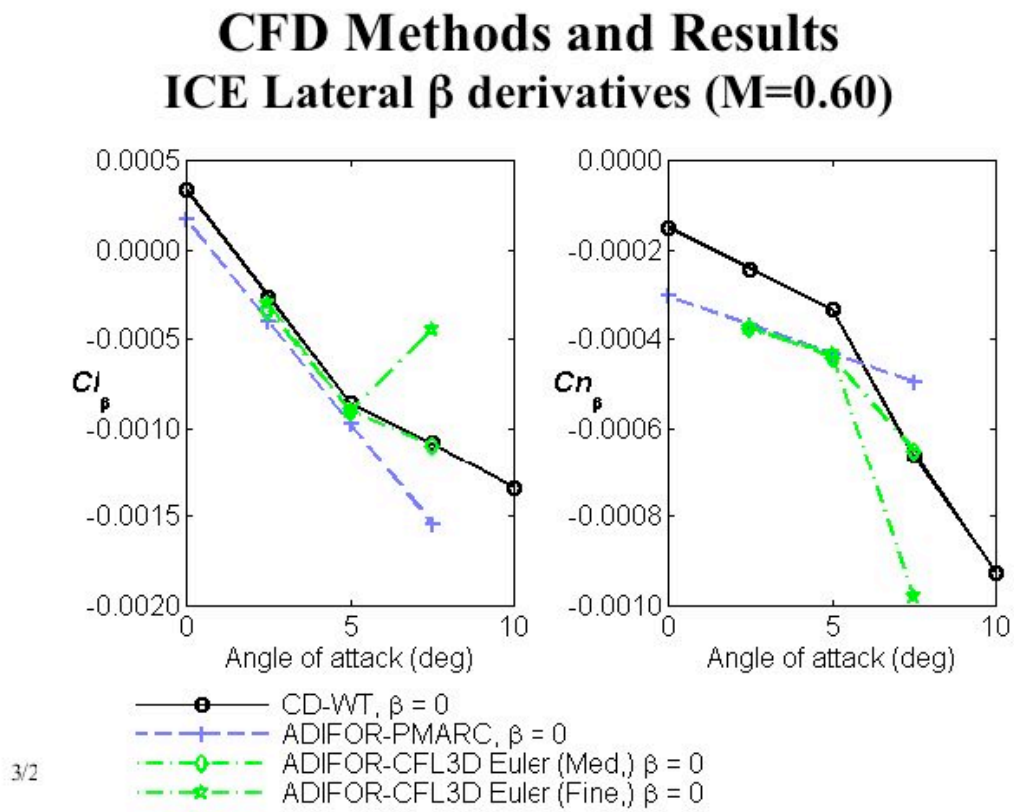


To move on to the lateral derivatives.

The derivatives of side force coefficient with respect to angle of sideslip or beta is shown on the vertical axis. Only the inviscid ADIFOR-CLF3D Euler is shown because the viscous cases were performed with a half span model and therefore cannot show the lateral derivatives. The Euler code does not nail the derivatives exactly, but does detect the break in the data above 5 deg angle of attack.



The left graph depicts the derivative of rolling moment coefficient with respect to angle of sideslip on the vertical axis. The right graph depicts the derivative of yawing moment coefficient with respect to angle of sideslip on the vertical axis. The ADIFOR-CFL3D maybe seeing derivative values that are underestimated by the large step in the wind tunnel central differencing calculation or the asymmetry in the wind tunnel data.

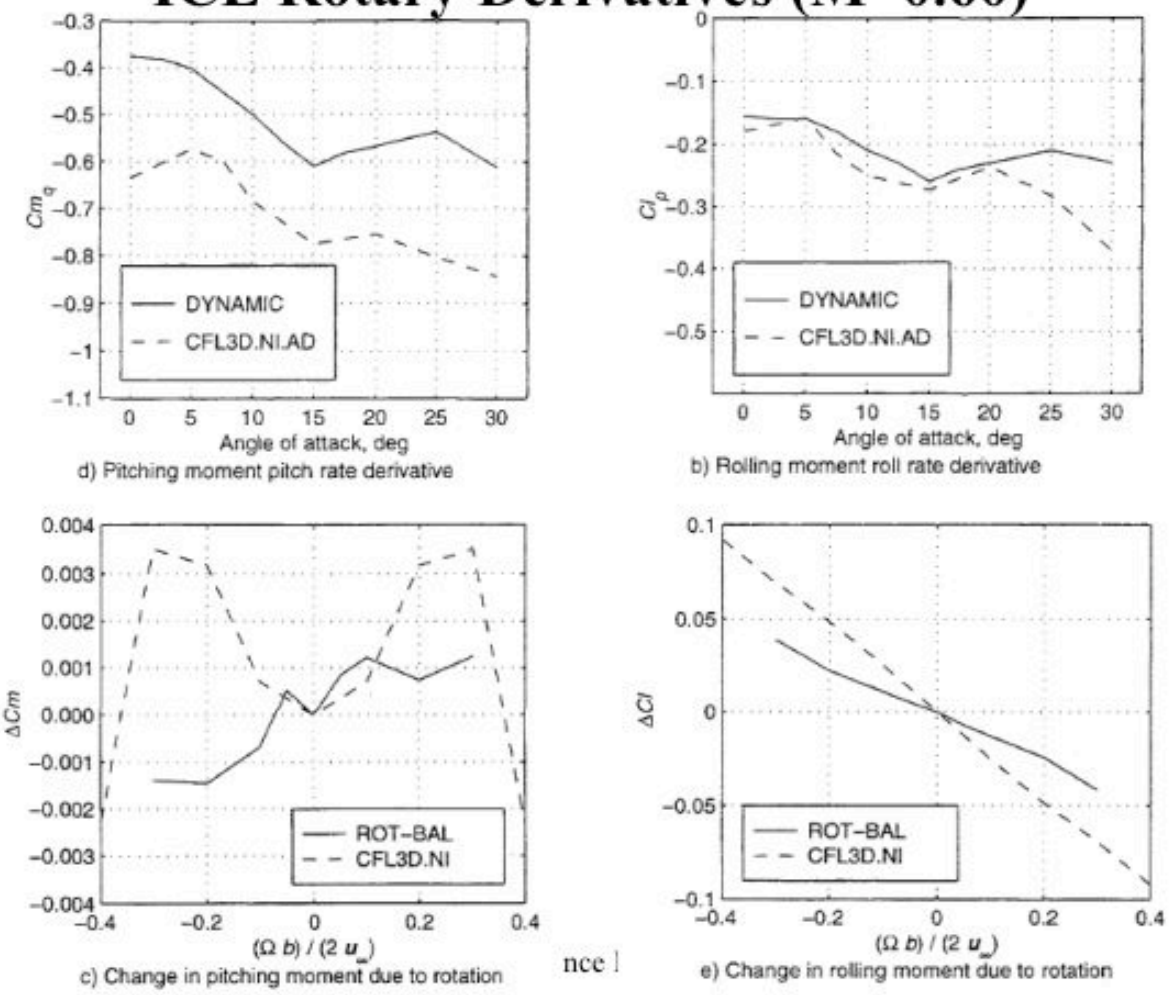


3/2

This figure illustrates our attempts to compute roll rate derivatives and pressure increments to compare with rotary balance data with a Navier-Stokes code. The agreement is generally good, but the anomalous results for delta CM in the rotary balance comparison have not been unexplained.

CFD Methods and Results

ICE Rotary Derivatives (M=0.60)



The types of comparisons done, and the resulting accuracy to which derivatives were obtained are pointed out. Note that even "poor" comparisons were better than other previous linear aerodynamic approximations. Note the time required to obtain solutions and the memory required.

CFD Methods and Results

CFL3D Data Summary, ICE Configuration

Description		Performance in Different Flow Structures		
		Attached	**Vortical Bursting**	
		0–5α	**6–15α**	**>15α**
Forces and moments	(***Cm***)	Excellent	Excellent	Good
Long. Static stability	(Cm_α)	Excellent	Excellent	Good
Lat. / Dir. Static stability	(Cl_β)	Excellent	Good	Poor*
Quasi-Dynamic derivatives	(Cl_p)	Excellent	Excellent	Good

Dynamic derivatives **current & ongoing work**

CFL3D.NI.AD, 0-15 deg α	**30** hr. per angle of attack case
CFL3D.NI.AD, >15 deg α	**90** hr. per angle of attack case
Center-difference CFL3D.NI 0-15 deg α	**44** hr. per angle of attack case

Execution on 16-processor SGI Origin 2000™ with 12 Gb RAM

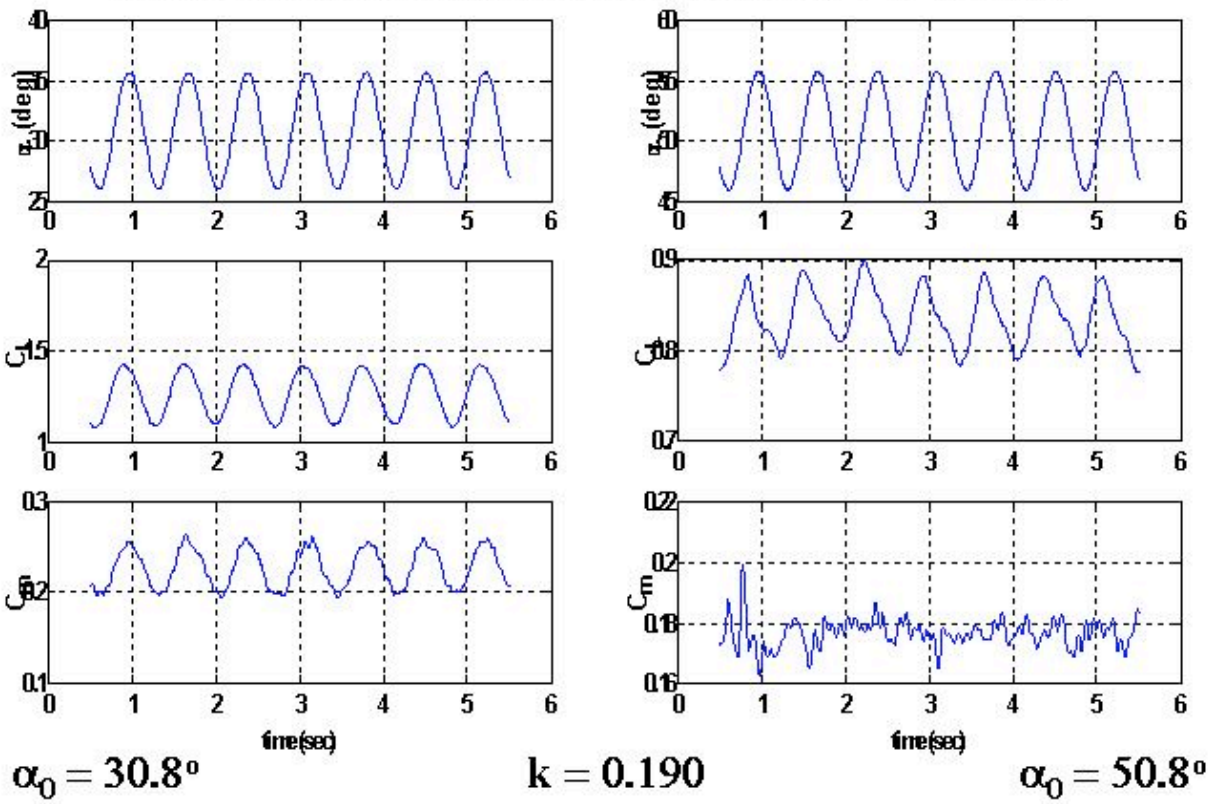
* Still better than previous capability

PMARC generally one grade less than CFL3D ~ 1/3 hour per point or less

This figure illustrates the lift and moment coefficients time histories in response to an imposed small amplitude (5 degree) oscillation of the angle of attack, as measured in the 12 Foot Low Speed Wind Tunnel. The moment response, which is directly related to the surface pressure distribution, illustrates the rapidly changing characteristics of the vortical and bursting flows at 30.8 and 50.8 degrees mean value of alpha. PMARC time histories for the lift were similar, but the moment differed considerably, and required further study.

CFD Methods and Results

Measured Dynamic Data (NASA TM 97-206276)



The traditional wind tunnel technique for the separation of lumped derivatives is to use both a curved flow wind tunnel to identify pitch rate effects and plunge motions to identify angle of attack effects, neither of which are common experimental techniques today. In 1999, the Park/Green paper proposed that CFD offers the potential to computationally separate lumped dynamic S&C derivatives, but the technique was neither developed, nor demonstrated, at that time. Recently, I have proposed three techniques to computationally separate lumped dynamic S&C derivatives. The first technique applies the usual data processing techniques for wind tunnel data to the CFD time histories. If static and pure rotary data are available, an algebraic manipulation can be used to extract force and moment derivatives with respect to alpha-dot and

CFD Methods and Results

"Lumped" Dynamic S&C Derivatives

- Dynamic S&C derivatives are measured in combinations during forced-oscillation wind tunnel tests (NASA / TM-97-206276)

In phase component: $\bar{C}_{L\alpha} = C_{L\alpha} - k^2 C_{L\dot{q}}$

Out of phase component: $\bar{C}_{Lq} = C_{Lq} + C_{L\dot{\alpha}}$

- The traditional wind tunnel answer to derivative separation: curved flow tunnel / plunge experiments – these capabilities are no longer available at NASA LaRC
- CFD offers the potential to computationally separate lumped dynamic S&C derivatives
  - Technique 1: Process CFD time history like wind tunnel data
  - Technique 2: Solve two simultaneous equations for two unknowns at each time step; integrate results over time
  - Technique 3: algebraic variant of Technique 2

q-dot. The second and third derivative separation techniques involve the solution of two simultaneous equations for these same alpha-dot and q-dot derivatives.

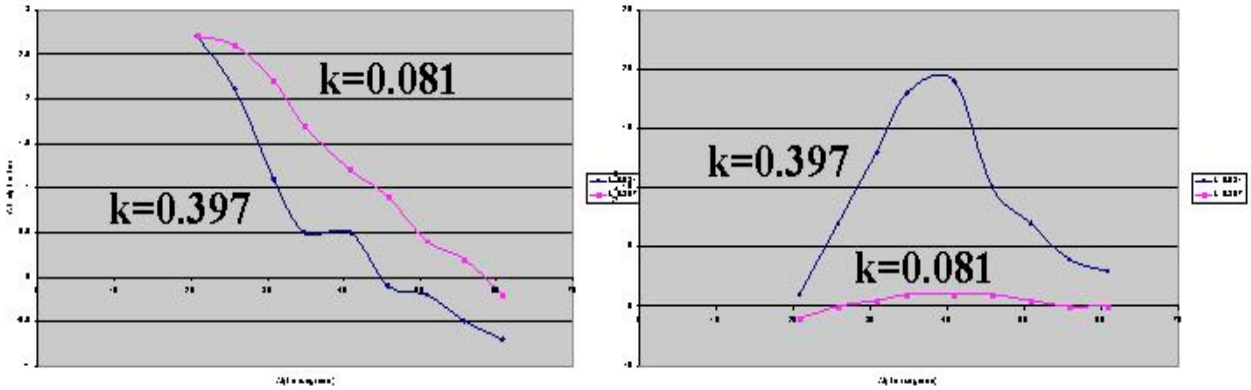
This figure shows the typical so-called in-phase and out-of-phase lumped dynamic derivative response for the lift force during forced pitch oscillations at various k rates.

S&C Background

"Lumped" Dynamic S&C Derivatives, 10% scale F-16XL

In-phase lumped derivative: $\bar{C}_{L\alpha} = C_{L\alpha} - k^2 C_{L\dot{q}}$

Out-of-phase lumped derivative: $\bar{C}_{Lq} = C_{Lq} + C_{L\dot{\alpha}}$



In-phase lift lumped derivative

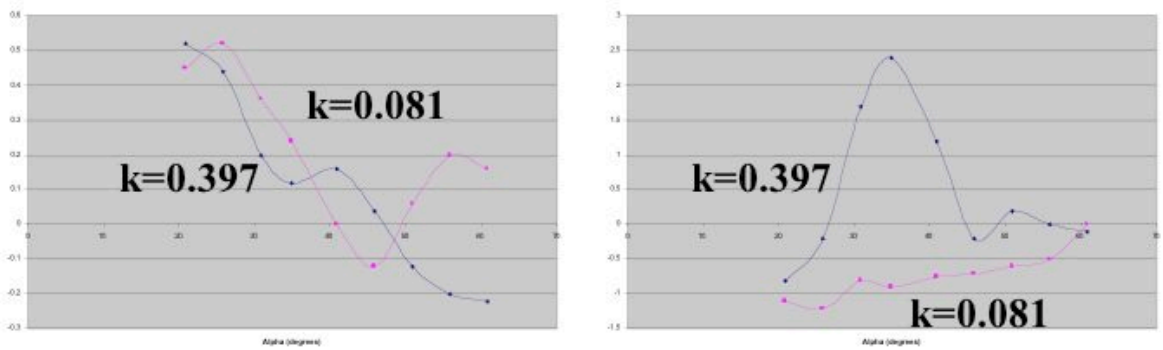
$k = \frac{\omega \bar{c}}{2V}$

Out-of-phase lift lumped derivative

This figure shows the typical so-called in-phase and out-of-phase lumped dynamic derivative response for the pitching moment during forced pitch oscillations at various k rates.

CFD Methods and Results

"Lumped" Dynamic S&C Derivatives, 10% scale F-16XL

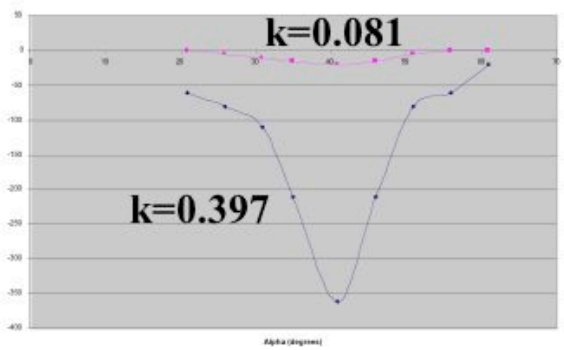


In-phase moment lumped derivatives $k = \frac{\omega \bar{c}}{2V}$ Out-of-phase moment lumped derivative

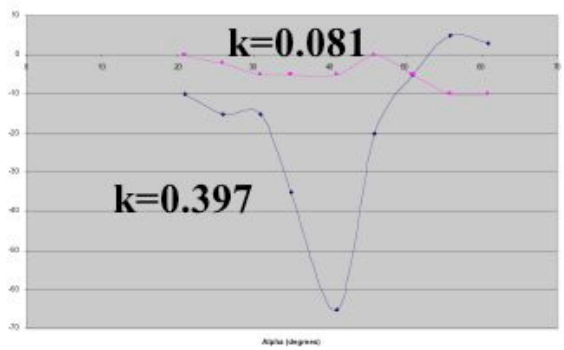
This is an example of computational separation of lumped dynamic derivatives using separation technique 1. Measured data was processed as usual. Then algebraic manipulation was used to extract the q-dot derivatives. The derivative CL-q-dot is shown in the left hand figure for various k rates; the derivative CM-q-dot is shown in the right hand figure.

CFD Methods and Results

Technique 1 Separation of "Lumped" Dynamic S&C Derivatives



In-phase
lift response



In-phase
moment response

$$k = \frac{\omega \bar{c}}{2V}$$

To summarize, conventional S&C modeling and experimental techniques are generally good for steady, low to moderate vehicle orientations, and perhaps mild separation, but have notable limitations in transonic, or fully separated flows. CFD offers capabilities complimentary to the conventional S&C techniques. Several methods for the application of CFD to S&C have been discussed, including the computation of forced oscillation motions, the computation of lumped dynamic S&C derivatives, and several computational separation techniques for use with lumped dynamic S&C derivatives. All of these steps are important to establish the credibility of CFD in the S&C arena. Additional detail on all these topics will be presented in the two pending papers which have been accepted for presentation at the Reno 2004 meetings.

Summary

- Conventional S&C modeling and experimental techniques
  - Generally good for steady, low to moderate orientations, mild separation
  - Notable limitations in transonic or fully separated flows
- CFD offers capabilities complimentary to conventional S&C
- CFD techniques for S&C discussed:
  - Computation of static and steady rate derivatives
  - Computation of dynamic S&C derivatives (forced oscillation motions)
  - Computation of lumped dynamic S&C derivatives
  - Computational separation of lumped dynamic S&C derivatives
  - Important steps to establish the credibility of CFD in S&C arena
- Additional detail on dynamic S&C techniques in AIAA 2004-0015 and 2004-0377 (Reno 2004)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01- 04 - 2004

2. REPORT TYPE
Conference Publication

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
COMSAC: Computational Methods for Stability and Control

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Fremaux, C. Michael and Hall, Robert M. (Compilers)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
23-762-45-AF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18378A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CP-2004-213028/PT1

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 08
Availability: NASA CASI (301) 621-0390 Distribution: Nonstandard

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://ntrs.nasa.gov

14. ABSTRACT

The unprecedented advances being made in computational fluid dynamic (CFD) technology have demonstrated the powerful capabilities of codes in applications to civil and military aircraft. Used in conjunction with wind-tunnel and flight investigations, many codes are now routinely used by designers in diverse applications such as aerodynamic performance predictions and propulsion integration. Typically, these codes are most reliable for attached, steady, and predominantly turbulent flows. As a result of increasing reliability and confidence in CFD, wind-tunnel testing for some new configurations has been substantially reduced in key areas, such as wing trade studies for mission performance guarantees. Interest is now growing in the application of computational methods to other critical design challenges. One of the most important disciplinary elements for civil and military aircraft is prediction of stability and control characteristics. CFD offers the potential for significantly increasing the basic understanding, prediction, and control of flow phenomena associated with requirements for satisfactory aircraft handling characteristics.

15. SUBJECT TERMS
Stability and Control; Computational Fluid Dynamics; Stability Derivatives; Aerodynamics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
U	U	U	UU	385	19b. TELEPHONE NUMBER *(Include area code)* (301) 621-0390

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18