Stability and Control in Computational Simulations for Conceptual and Preliminary Design

the past, today, and future?

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Introductory comments

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”

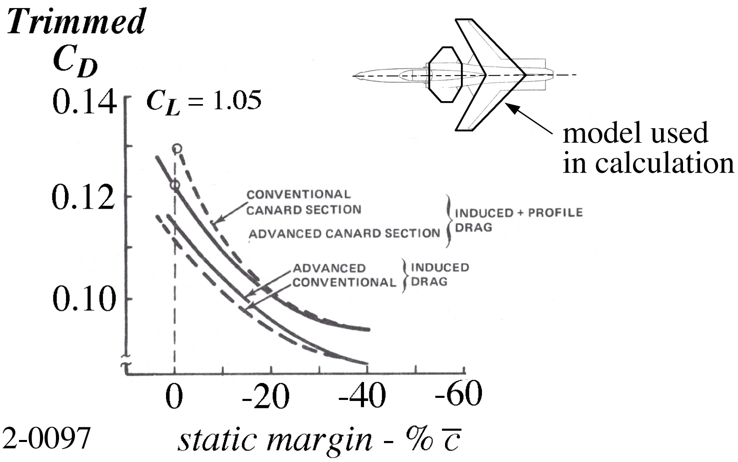
Exaggerated? —Not That Much!

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.

“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

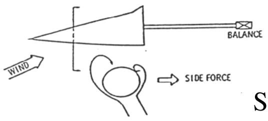
“Linear” aero finds the close connection between performance and dC_m/dC_L: the X-29

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.

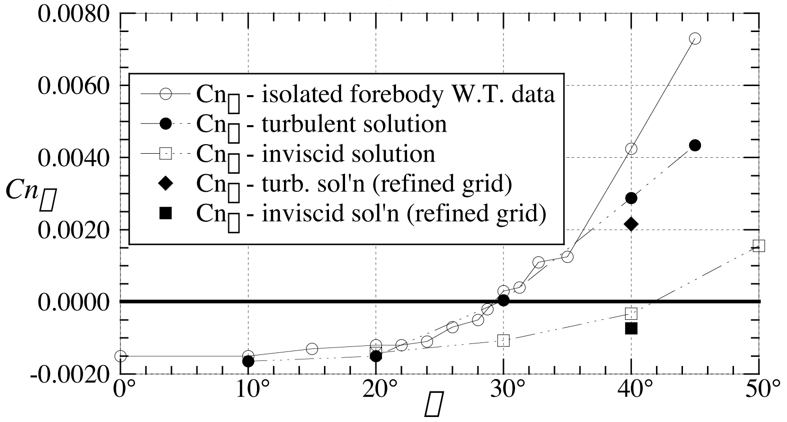
With the introduction of fly-by-wire and relaxed static stability concepts to increase vehicle performance, stability and control needed to become an essential part of the early design process. This was done when longitudinal stability was connected to the trimmed drag of the airplane to determine the 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

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.

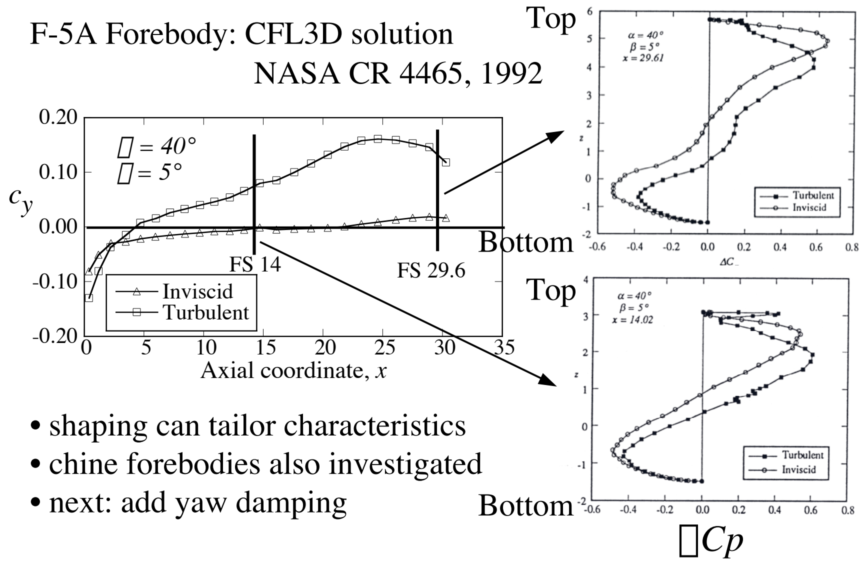
Nonlinear CFD study captures the F-5 directional stability from the Forebody

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.

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

F-5A Forebody: CFL3D solution
NASA CR 4465, 1992



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

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.

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.

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.

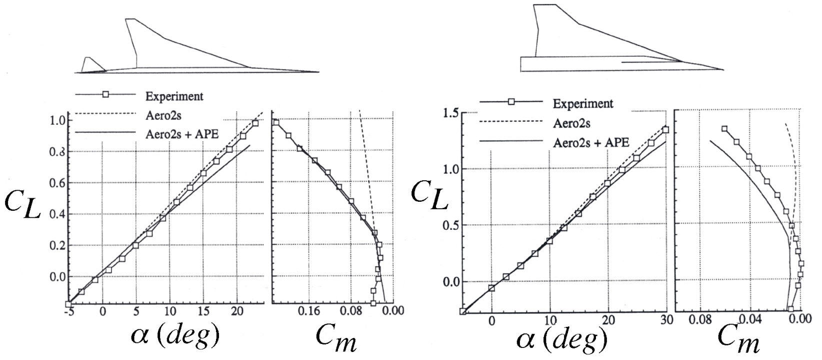
Mason, W.H., Knill, D.L., Giunta, A.A., Grossman, B., Haftka, R.T. and Watson, L.T., “Getting the Full Benefits of CFD in Conceptual Design,” AIAA 16th Applied Aerodynamics Conference, Albuquerque, NM, AIAA Paper 98-2513, June 1998.

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.

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

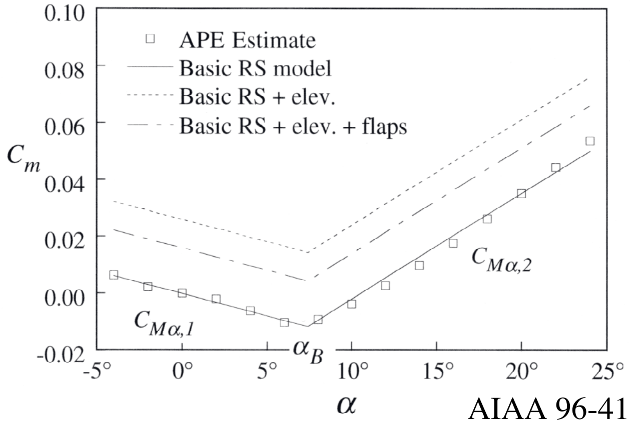
AIAA Paper 94-1819

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.

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

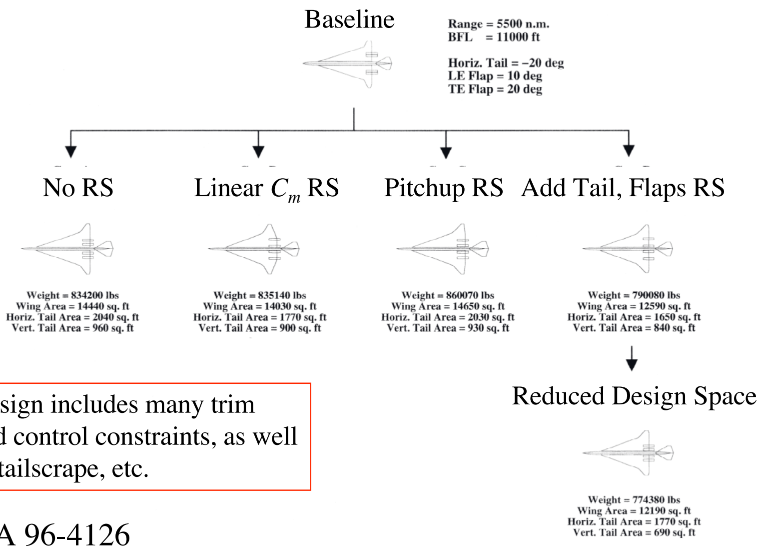


AIAA 96-4126

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.

MDO Results: An HSCT study



Baseline

Range = 5500 n.m.
BFL = 11000 ft

Horiz. Tail = −20 deg
LE Flap = 10 deg
TE Flap = 20 deg

No RS

Weight = 834200 lbs
Wing Area = 14440 sq. ft
Horiz. Tail Area = 2040 sq. ft
Vert. Tail Area = 960 sq. ft

Linear C_m RS

Weight = 835140 lbs
Wing Area = 14030 sq. ft
Horiz. Tail Area = 1770 sq. ft
Vert. Tail Area = 900 sq. ft

Pitchup RS

Weight = 860070 lbs
Wing Area = 14650 sq. ft
Horiz. Tail Area = 2030 sq. ft
Vert. Tail Area = 930 sq. ft

Add Tail, Flaps RS

Weight = 790080 lbs
Wing Area = 12590 sq. ft
Horiz. Tail Area = 1650 sq. ft
Vert. Tail Area = 840 sq. ft

Reduced Design Space

Weight = 774380 lbs
Wing Area = 12190 sq. ft
Horiz. Tail Area = 1770 sq. ft
Vert. Tail Area = 690 sq. ft

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

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.

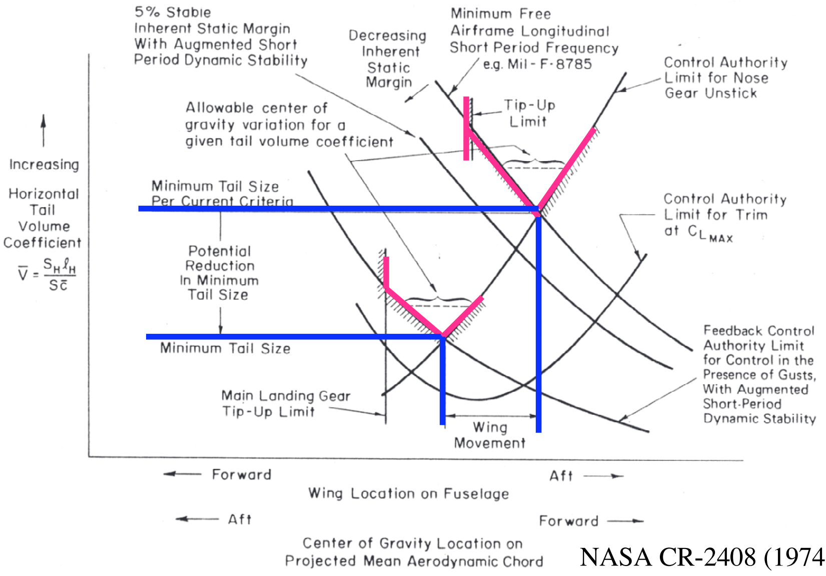
The final development of this methodology was described in the paper by Pete MacMillin, et al:

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.

Stability and Control in Tail Sizing: RSS/Active Controls



NASA CR-2408 (1974)

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.

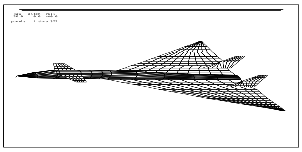
Conceptual/Preliminary Design Tools

- 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

Conceptual/Preliminary Design Tools

Example of “Scorecard” Validation: the XB-70

AIAA 95-0759



Stability derivatives

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

Control derivatives

Derivative	$C_{L\square f}$	$C_{m\square f}$	$C_{n\square f}$	$C_{l\square f}$	$C_{L\square c}$	$C_{m\square c}$	$C_{Y\square r}$	$C_{n\square r}$	$C_{l\square r}$
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

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#Control Power

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.

Needs

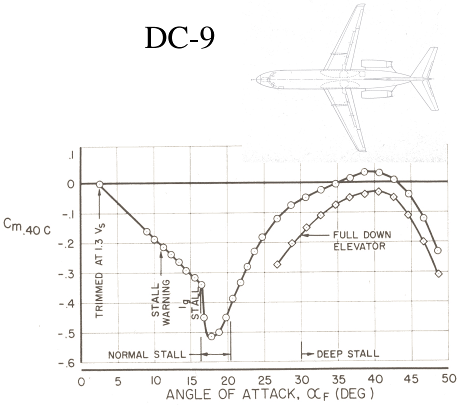
- Geometric Flexibility
- Rapid Analysis
- Various fidelity analyses
- Software designed for MDO
- Validation/Risk reduction

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

Needs

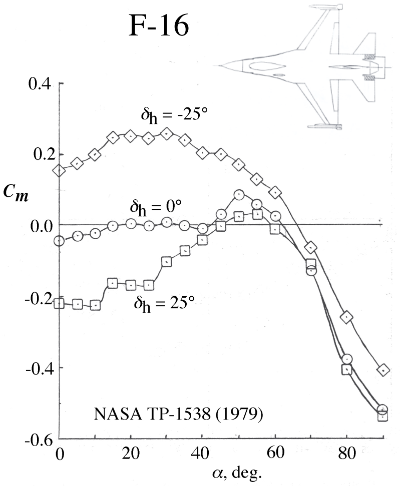
CFD Challenge Problems

DC-9



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

F-16



NASA TP-1538 (1979)

CFD Challenge Problems

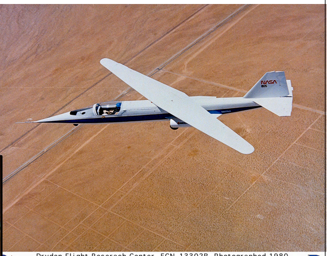
These famous pitchup and deep stall cases, one for a T-tail transport aircraft and one for a fighter with strakes, illustrate critical characteristics that need to be understood early in the design phase. They also illustrate the complexity of the challenge. The critical conditions are associated with 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).

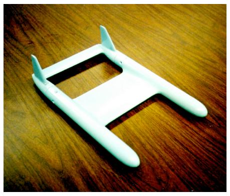
DC-9 pitching moment: Shevell, R.S., and Schaufele, R.D., “Aerodynamic Design Features of the DC-9,” *Journal of Aircraft*, Vol. 3, No. 6, Nov.-Dec. 1966, pp. 515-523.

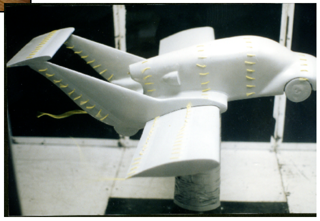
Advanced concepts are “non-standard” leading to new computational challenges

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



Dryden Flight Reserach Center ECN-13302B Photographed 1980
AD-1





Advanced concepts are “non-standard” leading to new computational challenges

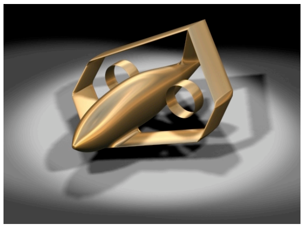
The concepts here include a strut braced wing on an A-7, as proposed for REVCON a few years ago, and which required special transonic analysis of the wing-pylon-strut junction (Andy Ko, W.H. Mason and B. Grossman, “Transonic Aerodynamics of a Wing/Pylon/Strut Juncture,” 21st AIAA Applied Aerodynamics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

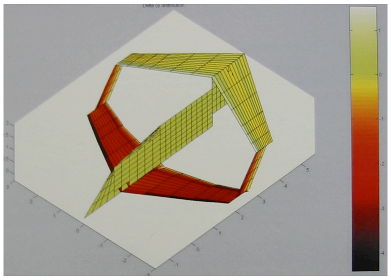
Another concept is Leroy Spearman’s “Inboard Wing” concept, which requires modeling the “tip vortex” when the wing has fuselage “end plates”

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.

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

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.

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)

Potential Approaches

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

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

Godfrey, Andrew G, and Cliff, Eugene M,, "Direct calculation of aerodynamic force derivatives - A sensitivity-equation approach," 36th Aerospace Sciences Meeting & Exhibit, 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

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