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

![Graph showing trimmed CD vs. static margin]

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
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.

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 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.


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 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.


See also:

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

Application to Design

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

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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.


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


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.


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

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:


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.


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


Dynamic stability derivative predictions from Digital DATCOM were by Blake:


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
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.


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.


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

  - *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)

• 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.


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