Investigations in Reduced-Order Aerodynamic Modeling of Aircraft Approaching Stall

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Outline

• Background and Motivation

• Current Approach for Generating Flight Simulation Models

• Stall Model Augmentation via CFD

• Opportunities & Challenges for Reduced-Order Modeling (ROM)

• Summary
Background and Motivation

• Aircraft Loss of Control (LOC)
  – Leading contributor to fatal accident rate of commercial transports
  – Significant percentage of LOC events have involved stall

• Risk reduction via:
  – Accident analysis → hazard identification → proposed mitigation strategies
  – New regulatory requirements include pilot training for full stall recovery
  – Interest in improved modeling of transport airplane stall dynamics

• Purpose of this presentation
  – Present current status and challenges of ongoing work in leveraging CFD data for development of stall simulation models
  – Promote discussion within S&C modeling community towards addressing these challenges in future collaborations and workshops
LOC Risk Reduction Efforts

• NASA research for LOC mitigation
  – Supported by Technologies for Airplane State Awareness (TASA) under Airspace Operations and Safety Program (AOSP)
  – Purpose: Establish modeling requirements to enable full-stall training

• Flight Simulator Stall Modeling
  – Model designed to be representative of a T-tail airplane
  – Focus on dominant pilot-perceived characteristics of stall dynamics

• Exploring cost-effective ways to extend aerodynamic models into the stall regime for improved flight simulator training
  – Low-cost wind-tunnel and water-tunnel tests
  – Computational simulations
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Stability-Derivative Flight Dynamics Model

$$C_{l_{\text{total}}} = C_l(\alpha, \beta) + \Delta C_{l_{\text{ail}}}(\alpha, \beta, \delta_a) + \Delta C_{l_{\text{rud}}}(\alpha, \beta, \delta_r) + \Delta C_{l_{\text{spL}}}(\alpha, \beta, \delta_{\text{spL}})$$
$$\quad + \Delta C_{l_{\text{spR}}}(\alpha, \beta, \delta_{\text{spR}}) + \Delta C_{l_{\text{asym}}}(\alpha, \beta) + C_{l_p}(\alpha, \dot{\alpha}) \hat{\dot{\alpha}} + C_{l_{\hat{r}}}(\alpha, \hat{r}) \hat{\dot{r}}$$

Current approach seeks low-cost aerodynamic data sources
Generic T-tail Transport (GTT)

- Representative T-tail regional jet
- Several low-speed wind tunnel models
- CFD used to understand and augment stall model
- Subscale flight vehicle (currently open to support)
  - Potential validation case

<table>
<thead>
<tr>
<th>Reference</th>
<th>Full-Scale Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{c}$</td>
<td>11 ft.</td>
</tr>
<tr>
<td>$b$</td>
<td>76 ft.</td>
</tr>
<tr>
<td>$S$</td>
<td>754 ft.$^2$</td>
</tr>
<tr>
<td>$W$</td>
<td>55,847 lb.</td>
</tr>
</tbody>
</table>

GTT at Stall Condition
USM3D/SA, $\alpha=12^\circ$
Grid: 58M cells (full span)

GTT Designed by NASA and Area-I, Inc.
UAS and OML by Area-I, Inc. (info@areai.aero)
Low-Cost Experimental Data Sources for GTT

**Boeing R&T NAART**

2.0 % scale  
(span ~ 1.5 feet)

**NASA LaRC 12-Foot LST**

5.7 % scale  
(span ~ 4 feet)

**Boeing R&T Water Tunnel**

1.9 % scale  
(span ~ 1.3 feet)

$\alpha = 24^\circ$
GTT – Wind Tunnel and CFD Data
Static Solutions ($\beta = 0^\circ$)

CFD ...
1) corroborates qualitative S&C characteristics of WT data
2) can approximate ground-to-flight scaling effects
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Stall Model Augmentation with CFD

- **CFD Modeling Assumptions and Questions**
  - Approximate stall characteristics with URANS (due to cost)
  - How good is good enough for pilot-perceived stall characteristics?
  - How can CFD become a cost effective source for S&C data?

### Physical Testing
1. Physical measurement, not math model
2. Limits: low speeds, Reynolds numbers
3. Low-cost models thru 3-D printing
4. High rate of data generation

### Numerical Simulation
1. Ground-to-flight scaling
2. Interference-free simulations
3. Unrestricted simulated motions
4. Significant computational costs
SysID methods use specialty maneuvers to excite nonlinear, unsteady aerodynamics of interest for flight dynamics models:

- Regression of unsteady (indicial) response terms in aerodynamic model
- Rich history of use with wind tunnel and flight test data
- Maneuvers with wide frequency content & ranges of amplitudes

**Example Indicial Equation:**

\[ C_N(t) = C_N(0) + \int_0^t C_{N\alpha}(t-\tau) \frac{d\alpha}{d\tau} d\tau + \int_0^t C_{Nq}(t-\tau) \frac{dq}{d\tau} d\tau \]

SysID

- Model Postulation
- Specialty Inputs
- Parameter Estimation
- Model Structure
- Unsteady Aerodynamic Model

**How can CFD be leveraged as a data source?**

Discussed in AIAA 2018-3622 by Murphy, Wed. 3:00PM, Embassy C
Traditional Application of CFD with SysID

- CFD dynamic motion capabilities enable simulation of the complex flight maneuvers relevant to SysID
GTT Roll Damping with Reynolds Number
$Re_L = 0.27$ million & $16$ million

Derivatives from sinusoidal F-O

$C_{l,p}$ per rad

$\Delta \phi = \pm 5^\circ$

Unstable
Stable

CFD roll-damping derivatives using classic F-O technique
- Corroborate WT measurements
- Unfortunately requires days of computation per point
- Hence, not a practical approach
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Reduced-Order Modeling (ROM) and SysID

• Unsteady aerodynamic ROMs seek to match the predictive capability of full CFD simulations at significantly reduced computational cost
  – Constructed from high-fidelity CFD predictions of aerodynamic response to specialty maneuvers
    • Captures wide frequency content and nonlinear flow regimes
  – Sampled data reconstructed to quickly estimate response to arbitrary maneuvers at multiple flight conditions, (Mach number, frequency, etc.)
  – How is this related to SysID…?

• ROMs may be categorized as parametric or non-parametric
  – Parametric: Identification of indicial functions using assumed parametric model and training maneuvers, SysID applied to CFD data
  – Non-parametric: Identification of indicial functions using CFD motion capabilities to directly obtain indicial response (no training maneuvers)
Indicial Response (IR) ROM

- IR ROM is a non-parametric method investigated by USAFA, NATO AVT, and NASA Langley
  - Based on step (indicial) functions, which capture entire frequency spectrum of response
    - Not feasible to obtain in wind tunnels
    - Hence, the historical need for trained parametric models

- Why not use these ROMs in flight simulators today?
  - Requires demonstration of real-time ROM predictions
  - Would require step functions with respect to control surface deflections
    - Not a mainstream computational capability
  - If successful, would require changes to flight simulator model infrastructure

- Near-term, potential benefit in using IR ROM to efficiently generate input maneuvers typically used for SysID
  - Takes advantage of existing flight dynamic modeling structures
  - Wind tunnels would account for aerodynamics due to control surface inputs

How do IR ROMs make maneuver predictions?
IR ROM Generation

Locally linear indicial responses
NACA 0012, USM3D/SA, M=0.6

\[ C_{N,\alpha} \text{, } C_{N,q} \text{ (1/rad)} \]

\[ C_N(t) = C_N(0) + \int_0^t C_{N\alpha}(t-\tau) \frac{d\alpha}{d\tau} d\tau + \int_0^t C_{Nq}(t-\tau) \frac{dq}{d\tau} d\tau \]

Indicial Equation
Nonlinear Indicial Response ROM Predictions

- Nonlinear extension of *locally linear indicial responses* via DoE sampling and surrogate modeling improves prediction capability
  - Time-dependent version of classic aerodynamic databases

\[
C_j(t) = C_j(0) + \int_0^t C_{ja}(t-\tau, \alpha, M) \, d\alpha \, d\tau + \int_0^t C_{jq}(t-\tau, \alpha, M) \, dq \, d\tau + \int_0^t C_{kj}(t-\tau, \alpha, M) \, dr \, d\tau
\]

For \( j = L, D, m \) (lift, drag, pitching moment)

For \( k = Y, l, n \) (sideforce, roll & yaw moment)

*How can this capability be used for SysID?*

*SACCON* Lazy 8 Maneuver

"Fly" maneuver in seconds

Full CFD maneuver: 50,000 CPU hr.
Proposed CFD-based ROMs for SysID

Trajectory Generation for Vehicle-State Step Inputs

Dynamic CFD Step Simulations

CFD Indicial Responses

Indicial Response ROM over range of $\alpha$, $\beta$, and $M$

Typical SysID Specialty Inputs

SysID Flight Dynamics Model Identification

Aerodynamic response generated in seconds

What are the challenges for IR ROM generation?

Model Postulation

Parameter Estimation

Specialty Inputs

Model Structure

Sinusoidal

Schroeder

$C_{N\alpha}$, $C_{N\beta}$

(1/rad)
Challenges for IR ROMs at Stall

- IR ROMs previously investigated for “complex” maneuvers, but limited to weakly nonlinear flow regimes, i.e., $\alpha < 10^\circ$

- Transient aerodynamics arise near stall conditions…
  - Unsteady wake shedding
  - Currently investigating:
    - Filtering of IR for dominant stall char.
    - Stochastic treatment of IR to create stall predictions w/ uncertainty

- IR ROMs remain worthwhile topic of research due to:
  - Fundamental step response
  - No complex training maneuvers
  - No CFD solver modification
  - Nonlinear extensions available
Summary

• URANS CFD currently used to approximate stability-derivatives that augment GTT stall model in flight simulator
  – Forced oscillation damping derivatives being tested in simulator
  – Exploring alternative methods for efficient stability derivative calculations
  – Metric is pilot-perceived response to character of stall

• IR ROMs may provide a low-cost data source for simulating maneuvers required for Aircraft SysID methods
  – Step maneuvers difficult to physically test but enabled by CFD
  – Direct use in simulators would require real-time prediction via fast integration and efficient control surface modeling
  – Potential intermediate benefit for efficient generation of SysID inputs

• IR ROM challenges persist in unsteady flows near stall
  – Can artificial smoothing still capture pilot-perceived character of stall?
  – Can uncertainty principles be incorporated for improved prediction confidence?
Thank you
Questions?