SIMULATION MODELING FOR OFF-NOMINAL CONDITIONS – WHERE ARE WE TODAY?

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The modeling of aircraft flight characteristics in off-nominal or otherwise adverse conditions has become increasingly important for simulation in the loss-of-control arena. Adverse conditions include environmentally-induced upsets such as wind shear or wake vortex encounters; off-nominal flight conditions, such as stall or departure; on-board systems failures; and structural failures or aircraft damage. Spirited discussions in the research community are taking place as to the fidelity and data requirements for adequate representation of vehicle dynamics under such conditions for a host of research areas, including recovery training, flight controls development, trajectory guidance/planning, and envelope limiting.

The increasing need for multiple sources of data (empirical, computational, experimental) for modeling across a larger flight envelope leads to challenges in developing methods of appropriately applying or combining such data, particularly in a dynamic flight environment with a physically and/or aerodynamically asymmetric vehicle. Traditional simplifications and symmetry assumptions in current modeling methodology may no longer be valid. Furthermore, once modeled, challenges abound in the validation of flight dynamics characteristics in adverse flight regimes.

OUTLINE

- Off-Nominal Conditions
- Modeling in Current Training Simulations
- Current Modeling Research Activities
- Model Validation Issues
- Needs and Challenges; Future Activities

OFF-NOMINAL CONDITIONS CONSIDERED

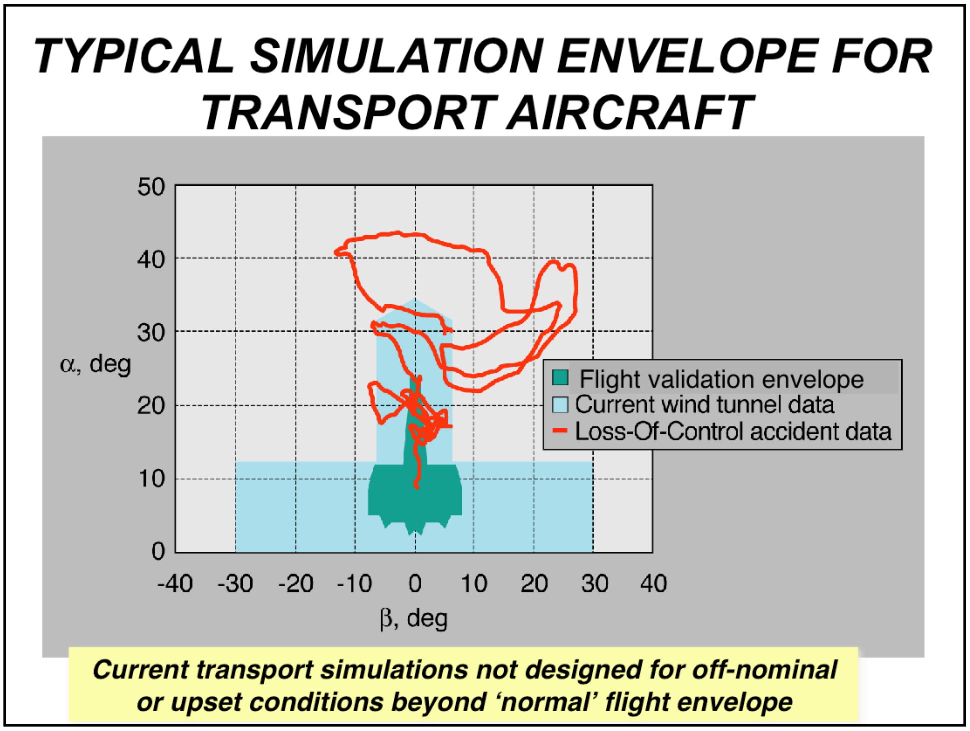
- Stall / High-angle-of-attack
  - $\alpha \geq$ stall warning (e.g., stick shaker)
- Failures / Damage
- Atmospheric / Environmental
  - Wind shear
  - Wake vortex
  - Icing

While there is a broad range of potential off-nominal conditions, the ones being considered in this briefing are listed here.

The first is high-angle-of-attack and stall conditions. The area of interest is the region starting at stall warning (stick shaker for example) and continuing up through actual stall. There is general agreement that below stall warning, the aerodynamic models are sufficiently accurate relative to actual flight characteristics in current simulations.

A second area involves failures or damage. For failures this can mean on-board systems or control surface failures, while damage refers to actual airframe damage or changes to the outer mold line.

Finally, off-nominal conditions can also include atmospheric or environmental influences to the aircraft flight dynamics, such as wind shear, wake vortex, or airframe icing.



This figure illustrates the current state of the art of modeling for large transport airplanes. Typically, the aerodynamic model is based on well-defined wind tunnel testing and supplemented by empirical data.

The blue region is the typical wind tunnel data envelope. The green area is the envelope within which some aerodynamic parameters (static or dynamic) are flight validated. The emphasis, particularly at high-alpha, is usually on longitudinal characteristics (e.g., CL-max, stall break, elevator control power. It should be noted that all aspects are not necessarily validated at every condition. Generally speaking, validation of lateral/directional aspects is limited, particularly at high-alpha.

However, as the red trace (an actual time history of a transport loss-of-control accident) shows, it is possible for a transport aircraft to get to a regime where no data were actually acquired, and the aerodynamic models are based possibly on either linear or constant extrapolation from known data. Thus there is a high potential for inaccurate prediction of flight behavior, especially in stall and post stall, where aerodynamic characteristics can be highly non-linear.

CURRENT TRAINING SIMULATIONS – HIGH-INCIDENCE ANGLES

- Angle of attack ≥ stall warning (e.g. stick-shaker)
- Static aero
  - Constant or linear extrapolation beyond wind-tunnel data envelope
  - Limited flight validation, primarily longitudinal
  - Experimental/analytical/computational-based
- Dynamic aero
  - Estimates generally empirical/analytical
  - Linear derivatives
  - Limited flight test data for validation
  - Constant or linear extrapolation is common

Modeling at high-incidence angles in current simulations is discussed here. To reiterate, in referring to off-nominal or high-incidence conditions, it is the region at and above stall warning that is of interest.

For static aerodynamics, as shown on the previous chart, once beyond the wind tunnel envelope, data are often either linear or constant extrapolations from the known dataset, and flight validation emphasizes the longitudinal characteristics. Overall, the basic static aero database is some combination of experimental, analytical, and computational data

For transport aircraft, dynamic characteristics are generally estimated from empirical methods and past experience. Experimental testing is usually not conducted. Damping characteristics are generally modeled as linear derivatives. Very limited flight test data is available for validation at high alpha, and, like the static aero, data are often either linear or constant extrapolations when getting beyond the known or validated dataset.

CURRENT TRAINING SIMULATIONS – FAILURE / DAMAGE

- 'Predictable' failures modeled
  - System failures (e.g., propulsion, hydraulic, electrical)
  - Inoperative or degraded-capability controls
    - Reduced deflection range
    - Reduced angular rates
  - Jammed or hardover controls
- Damage / OML changes generally not modeled or emulated

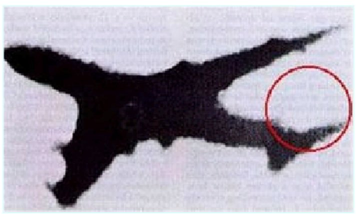
For failure situations, typical, expected types of failures are modeled, and many of them are based on certification requirements, like engine-out controllability, for example. In many cases, the resultant degradation in control capability is also modeled, for example with lower available hydraulic pressure a control surface may have limited range of travel and/or lower rate of motion. Frozen or hardover surfaces are also sometimes modeled.

The effects of significant damage or unexpected changes to the outer mold line, however, are generally not modeled.

TRANSPORT AIRCRAFT DAMAGE - EXAMPLES

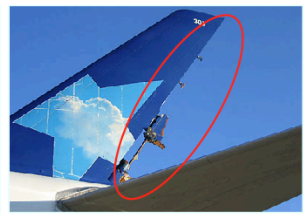
AA DC10 - 1979

- IAS Cargo B707 - 1977 - Horizontal Stabilizer Loss FATAL (6)
- AA DC10 - 1979 - Engine Separation/Wing Damage FATAL (272)
- JAL B747 - 1985 - Vertical Stabilizer Damage/Loss FATAL (520)
- EL AL B747 - 1992 - Engine Separation/Wing Damage FATAL (51)
- BA Concorde - 1989-2002 (5X) - Rudder damage/partial loss
- AA A300 - 2001 - Vertical Stabilizer Loss FATAL (265)
- DHL A300 - 2003 - Wing Damage/Flap Loss Hostile Act - Missile
- Air Transat A310 - 2005 - Rudder Loss



JAL B747 - 1985

DHL A300 - 2003



Air Transat A310 - 2005

However, as shown by these examples, there have been many instances of damage to transport aircraft, and many of those have resulted in crashes with large numbers of fatalities.

ATMOSPHERIC / ENVIRONMENTAL MODELING

- Wind shear – accepted and certified methods currently used in training
- Wake vortex – some modeling and training for encounter emulation conducted
- Icing modeling –
  - Process based on FAA Icing Handbook
  - Icing shapes developed/validated through experiment/computational methods (2D)
  - Shapes often mounted and tested in-flight for aero model development and validation (primarily GA and business aviation aircraft)

There are accepted and certified methods currently used for wind shear modeling in simulation.

Some modeling and training in aircraft response to wake vortex encounters is being conducted; this is currently a large research area.

Icing modeling is often dependent upon the specifics of the aircraft. The process of modeling and validating is often based on the FAA Icing Handbook. Icing shapes and aero characteristics are developed through combinations of experimental and computational means; mostly are based on 2-D airfoil geometry as opposed to 3-D swept wings. For primarily GA and business aircraft, validation is sometimes conducted with flight testing of ice shapes, in some cases even by flying in actual icing conditions. Research for icing on large transport swept wings is underway in the current NASA Aviation Safety Program, and future work in this area is also being planned.

CURRENT MODELING RESEARCH ACTIVITIES

- Experimental testing
  - α,β envelope expansion
  - Non-linear and dynamic modeling
  - Damage
- Computational Efforts
  - Dynamics modeling
  - Damage
- Icing

Activities for conducting research to expand our understanding and modeling for transport aircraft in off-nominal conditions are ongoing in a number of areas:

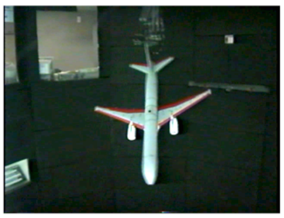
• Experimental work to expand knowledge throughout the alpha/beta envelope, consider the effects of non-linear aerodynamics and vehicle dynamics, and the effects of damage

• Computational efforts have been expanding into non-linear regimes, as well as dynamics modeling and damage characterization

• As mentioned earlier, research for icing on large transport swept wings is being conducted and planned in the NASA Aviation Safety Program

COMMERCIAL TRANSPORT MODEL TESTS

5.5% model on static mount
NASA LaRC 14x22 Ft Tunnel



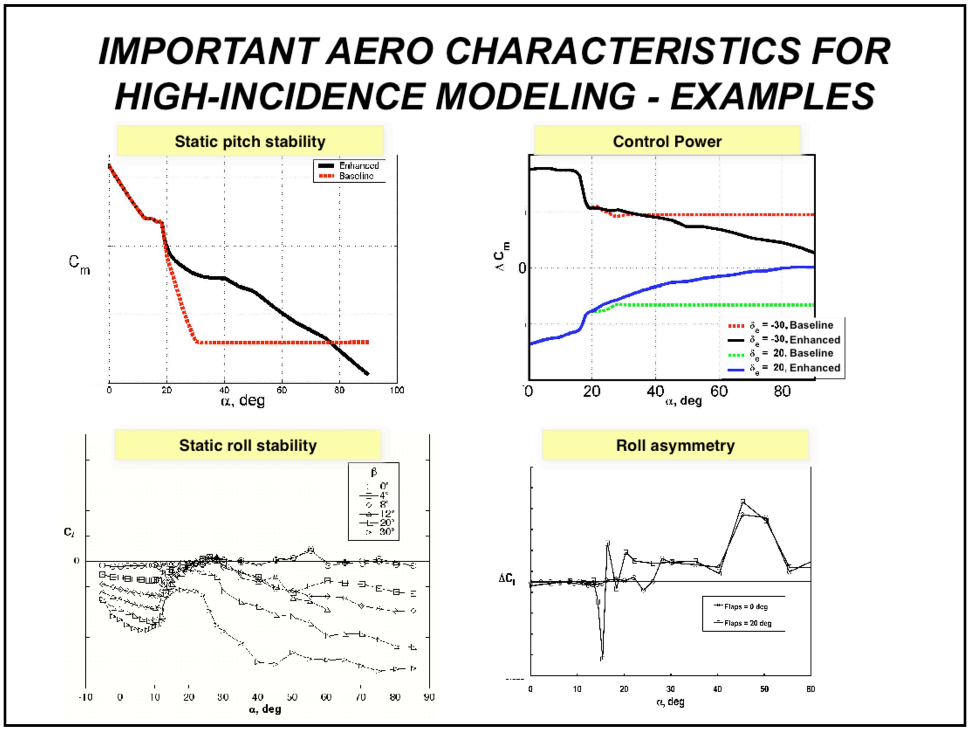
3.5% model on rotary balance rig
NASA LaRC 20 Ft Vertical Spin Tunnel

- ***Static***
  - 23,400 data points
  - α: -30 to 90°, β: -45° to +45°
  - Control and flap effects
  - Landing gear effects
  - Component effects
  - Failure conditions
- ***Forced Oscillation***
  - 3600 data points
  - α : -10° to 90°, β : -45° to +45°
  - Frequency and amplitude effects
  - Control and flap effects
  - Landing gear effects
  - Component effects
- ***Rotary Balance***
  - 16,000 data points
  - α : 0° to 90°, β : -45° to +45°
  - Rotational rate effects
  - Control and flap effects
  - Landing gear effects
- ***Free-Spin***
  - Dynamically-scaled
  - Simulation validation
- ***Flow Visualization***

5.5% model on roll forced oscillation rig
NASA LaRC 14x22 Ft Tunnel

Smoke/laser flow visualization in
NASA LaRC 12 Ft Tunnel

An unprecedented series of wind tunnel tests were conducted at NASA Langley Research Center in various facilities to closely examine aerodynamic characteristics at large angles of attack and sideslip, essentially to cover a broad range of the alpha/beta envelope seen earlier (note the alpha/beta ranges for each of the test methods). Over 46,000 data points were obtained using static and dynamic testing methods. These methods include dynamic test methods whereby the model undergoes motions in the wind tunnel to simulate highly dynamic motions that occur during loss-of-control accidents.



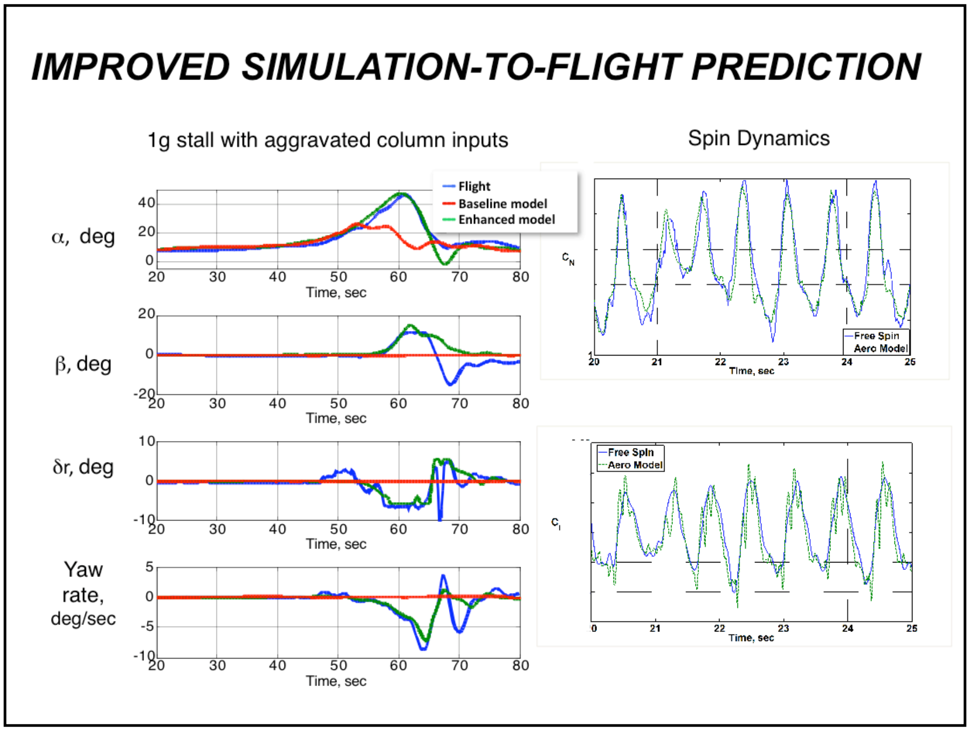
This chart illustrates some examples of non-linear aerodynamic behavior that must be modeled to accurately to predict flight dynamics in the stall regime. The non-linear nature of these data presents a challenge in measuring, modeling and validating these models.

Static pitch stability, as defined by the variation of pitching moment with angle of attack, is typically linear up to stick shaker and then may vary abruptly due initial wing separation and/or immersion of the horizontal tail in the wing wake. This example illustrates how the non-linear behavior causes the reduction in pitch stability (flattening of the curve) and the difficulty of extrapolating to high angles of attack.

The top right figure shows that actual elevator control power diminishes at high angle of attack, but is sometimes modeled as a constant value at those conditions, which can lead to an overprediction of available control capability during a recovery from a loss-of-control situation.

Static roll stability, as defined by the variation in rolling moment with sideslip, is typically linear but may vary with small changes in angle of attack approaching stall. In this example, static stability is unstable with small variation in sideslip angle but stabilizing at large angles, illustrating the need to capture the characteristics over a range of sideslip angles.

Due to the unstable nature of separate flow, roll asymmetries often appear at stall angles of attack. While research is still in progress to characterize these asymmetries, they can be due to asymmetric vortex positioning, slight lateral asymmetries in the outer mold line, rigging, or asymmetric stall. Nonetheless, asymmetries are needed to model roll-off tendencies and the large control inputs often observed during approaches to stall.

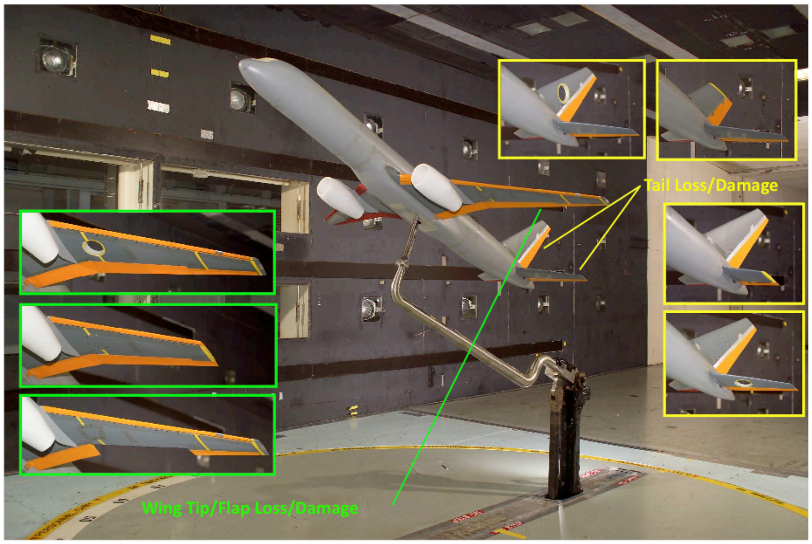


If one models the aforementioned additional characteristics into flight simulation, improvements in motion prediction can be realized.

The left figure is a time history of a transport aircraft 1-g stall with aggravated column inputs near stall. Note that this is an extreme case, the aircraft was maneuvered to an extremely high angle of attack, and the response (nose slice) is not necessarily typical of all transport aircraft at stall. Nevertheless, enhanced modeling reflects the actual flight time history much better, particularly in the resulting angle of attack as well as the lateral/directional excursions.

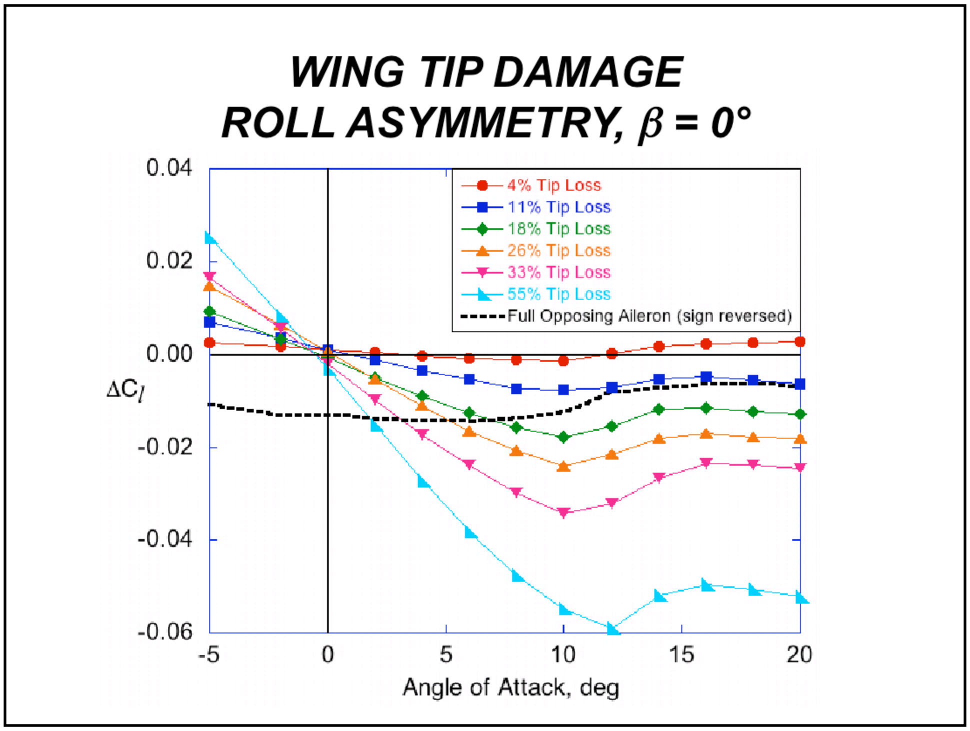
The right figure shows a comparison of an enhanced aerodynamics model with results from a free-spin wind tunnel test of a transport configuration.

DAMAGE MODELING



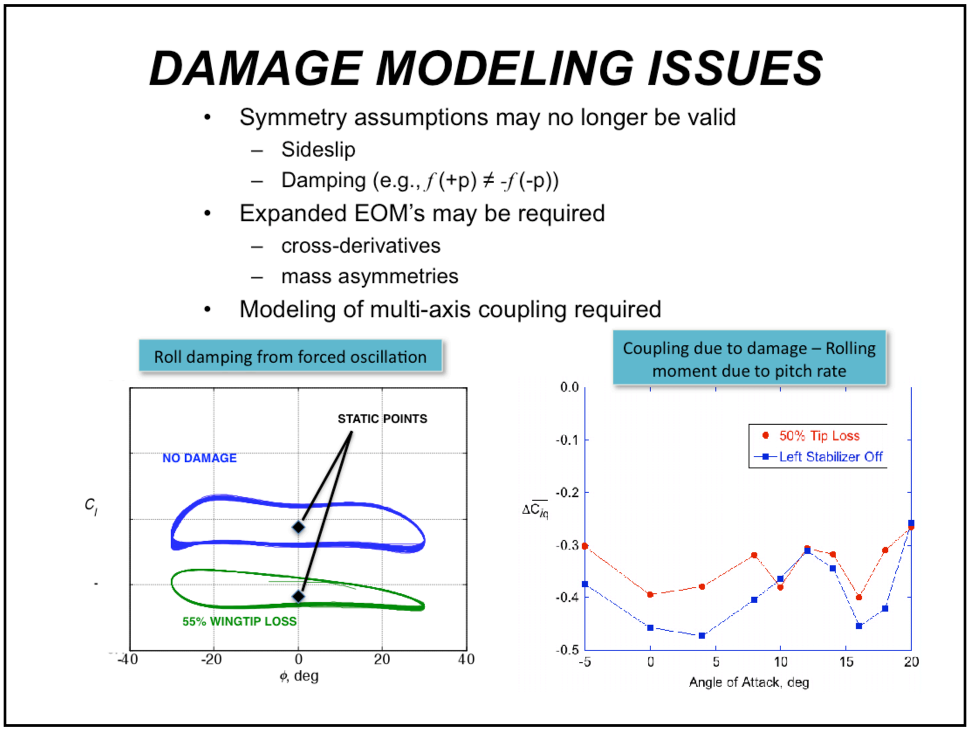
GTM Damage Modeling Tests – NASA Langley 14x22

As seen before, there have been many cases of aircraft damage resulting in major accidents. It is of course impossible to model all potential damage cases, therefore work has been done to evaluate systematic variations of damage to lift and control surfaces to study trends and identify stability and control boundaries. This figure shows the general types of damage conditions that have been experimentally tested.



An example of the resulting modeling data in the presence of damage is shown here, as the rolling moment increment due to progressively increasing loss of the left wingtip (in percent semispan).

Superimposed is the black dashed line which shows the available rolling moment from a full opposing aileron, and indicates boundaries in angle of attack due to rolling moment asymmetry.

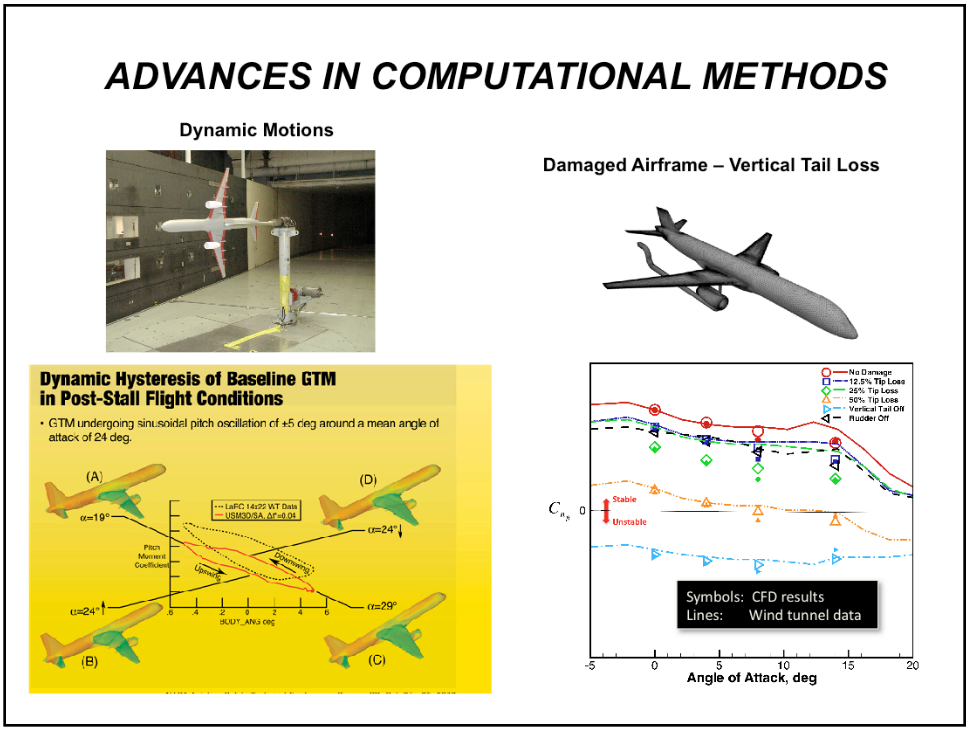


In addition to modeling the basic incremental aerodynamics due to damage, there are additional issues related to accurately modeling damage characteristics. Since damage will, in most cases, result in an asymmetric configuration, assumptions for symmetry in aerodynamic model structure (such as with sideslip or rate) may no longer be valid.

The left figure is one example- a time history of rolling moment versus roll angle for a damaged and undamaged case (wind tunnel data). The vertical distance between the static points and the time history lines reflect the amount of roll damping that exists. For the undamaged case, the damping is the same regardless of direction of motion. For the damaged case, however, that is no longer true, indicating that the dynamic characteristics will be different depending upon the direction of motion.

Asymmetries may result in cross-axis coupling which would not exist on a symmetric aircraft. The right figure is an example of this- rolling moment is generated by pitch rate in the presence of horizontal stabilizer damage. This value would be zero for a symmetric aircraft, and would not exist in a typical aerodynamic model.

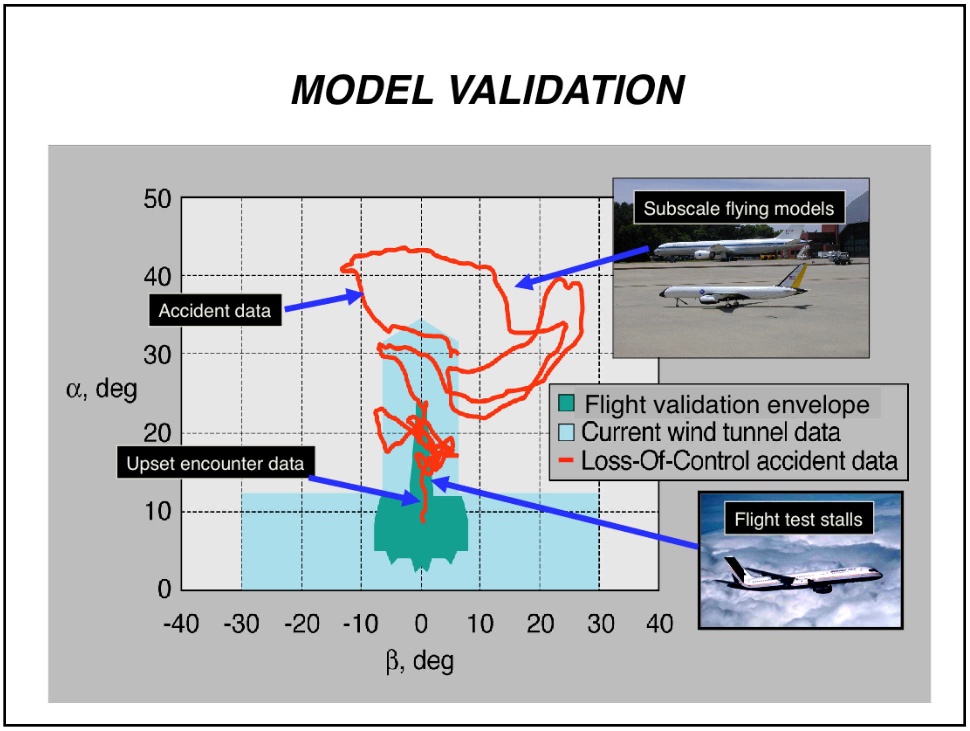
Asymmetric damage also means a shift in the center of gravity away from the aircraft centerline, meaning that simplified inertia matrices may no longer be used. Therefore, classical simplifications of the equations of motion based on symmetry assumptions would no longer be valid, and use of expanded or full equations of motion, as well as additional multi-axis dependencies, may be required.



Advances are being made in the computational aerodynamics in several areas, including dynamic motion at high angle of attack and damage effects.

The left figure shows comparison of wind tunnel forced oscillation data with CFD results at post-stall angles of attack, showing that CFD can be successful in the modeling of dynamic characteristics in off-nominal conditions.

The right figure shows CFD comparisons with wind tunnel tests of vertical tail damage on static directional stability. Symbols are CFD results (USM3D and FUN3D), lines are wind tunnel data.



Validation of aerodynamic modeling at extreme or off-nominal conditions is of course a continuing challenge. There are inherent difficulties in validating a large transport at such conditions (safety, structural, costs, etc.), and while we continually search for improved means of validation, there are some measures that are taken today as methods for use in different flight regimes, such as upset encounter or reconstructed accident data; flight test stalls and related maneuvers; or RPV's or subscale flying models in very extreme or accident conditions.

CURRENT CHALLENGES AND ISSUES

- Variations in transport airframe configurations
  - Tail arrangement
  - Wing geometry
- Model fidelity requirements
  - Generic vs type-specific
  - Cost of acquiring data
  - Response accuracy
- Validation of upset models
  - Stall / departure behavior
  - Apparent randomness

There are a number of additional challenges and issues in advancing modeling in off-nominal conditions.

In terms of configuration, how significant are certain configuration aspects in modeling in off-nominal conditions? For example, T-tail configurations would be expected to have different flight dynamics behaviors relative to conventional tail aircraft. Additionally, wing geometry (e.g., sweep, dihedral) can have large influences on some stability characteristics. Sensitivity in such areas may determine what level of testing or modeling is required.

This, then, leads to issues of model fidelity requirements:

•Can generic modeling be sufficient, or is type-specific modeling required to understand characteristics or provide training in off-nominal conditions?

•Costs of acquiring such data can drive requirements

•What level of vehicle response accuracy is necessary to model for training purposes? (e.g., nose slice, or reduced lateral stability)

And as discussed earlier, validation is a continuing challenge in this area.

SUMMARY AND CONCLUDING REMARKS

- Advances in modeling in off-nominal conditions are continuing
  - Experimental
  - Computational
- Challenges abound in many areas
  - Fidelity requirements
  - Validation
- Future modeling research activities will address challenges

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