Lessons from Modeling Flexible Aircraft for Active Flutter Suppression

JEFFREY OUELLETTE

NASA ARMSTRONG FLIGHT RESEARCH CENTER

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Active Flutter Suppression (AFS)

Reducing structural weight

- Standards require flutter to be 115% of maximum airspeed (Vne)
- Control system could be used to increase flutter speed without structural weight

Addressing design issues

- Predicted flutter speed can drop as design matures
- AFS could avoid expensive redesigns

X-56A Multi-Utility Technology Testbed

- Designed for testing active flutter suppression
- Flexible wings have unstable flutter modes
- AFRL Funded
- Lockheed Martin Built
- NASA has flown slightly past the flutter speed

Objective

Generate models useful for the <u>design</u> and <u>evaluation</u> of control laws for active structural control and flutter suppression that are able to accurately <u>predict</u> body freedom flutter.

For design

- Form of the models
  - State-space models
- Interpolation between flight conditions
  - Full envelope design

For evaluation

- Uncertainty
- Piloted simulation

Prediction

- Physically based models
  - Using information typically available before flight
- Predictive accuracy insufficient/inconsistent
  - Using flight test results to determine where we went wrong

Challenges with Aeroservoelastic Modeling

Challenging Dynamics
- Unstable
- Closed Loop

Model Complexity
- High Order
- Multiple-input
- Multiple-output

Nonlinearities
- Difficulty in prediction
- Difficulty in interpreting

Uncertainty and Noise
- Turbulence
- Limited Knowledge
- Variability

Types of models being used

NDoF model

- Preflight models
  - Did some updates from stiff wing data
- Very high order
  - ~300 states
- Integrated into piloted simulation

Low Order Equivalent System (LOES) models

- Transfer functions
  - Different from handling qualities LOES
- Lower order system
  - Do have structural modes
- Flight derived
  - Time domain system ID

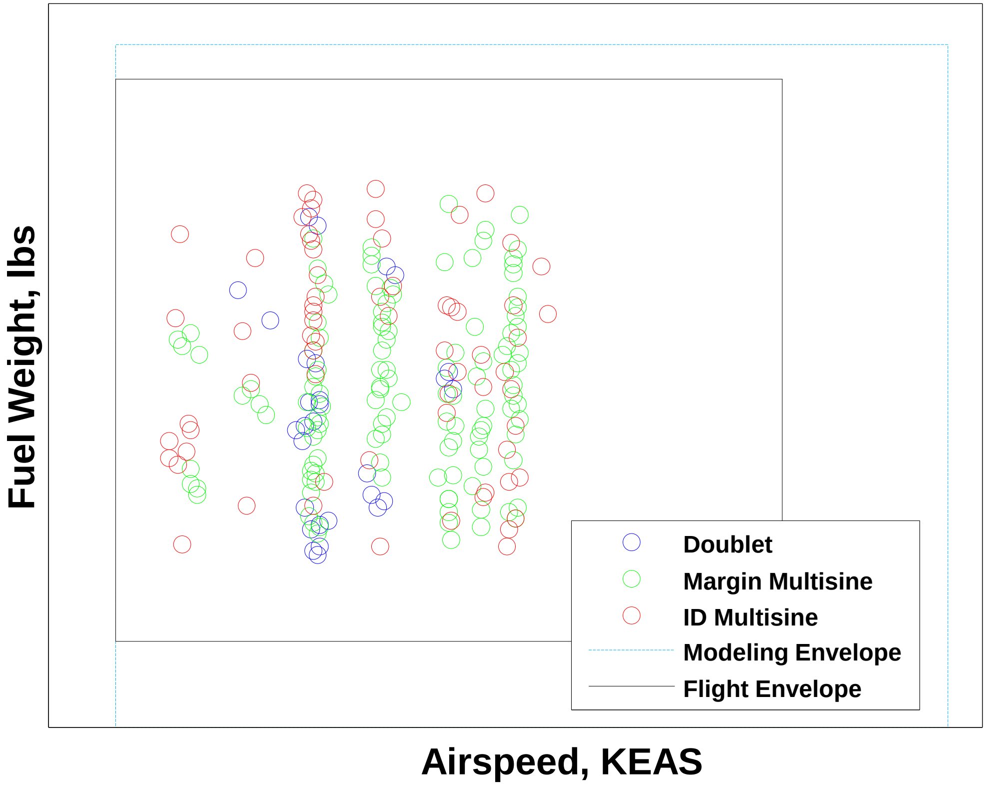
Parameter estimation models

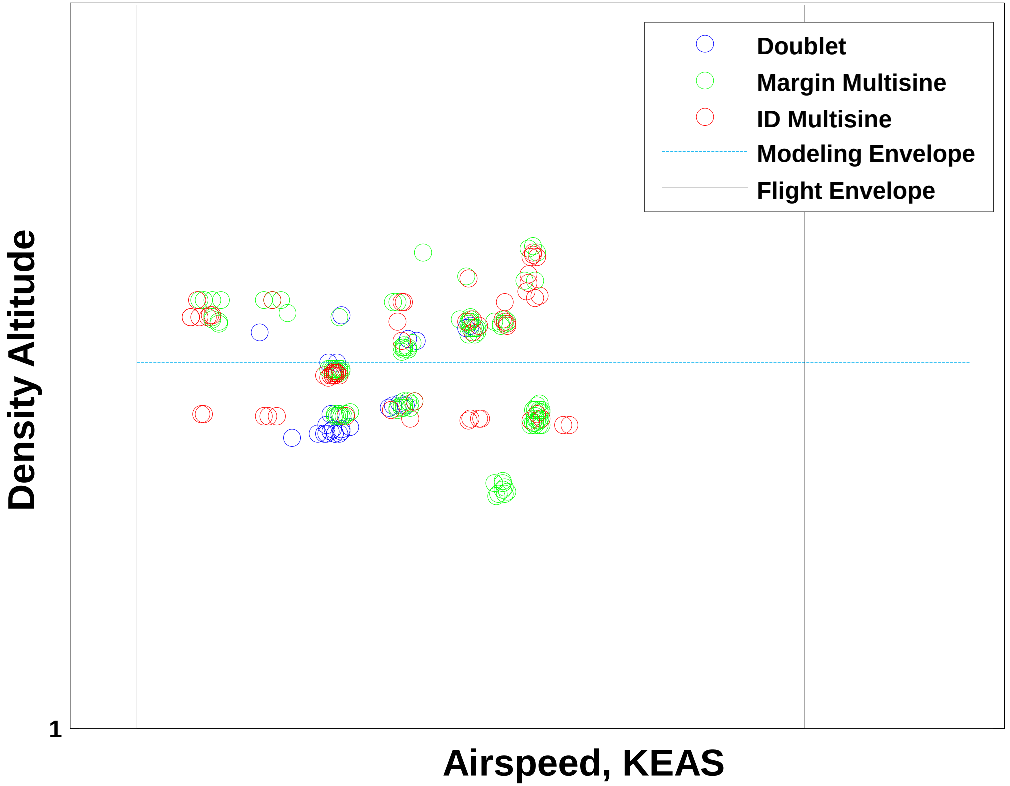
- Lower order
- Flight derived
- More physical parameters
- Still in development

Frequency responses

- Flight derived
- Non parametric (high order)

Maneuvers Used





Use air density in place of altitude
- Small effect for low subsonic conditions

Use ID multisines for updating
- Better excitation for system ID

Use margin multisines for validation
- Keeps data independent of tuning
- Plenty of test points for comparison
- Compares specific input/outputs of interest

Model Complexity: “Curse of dimensionality”

HIGH ORDER MODELS

MIMO SYSTEM

Aeroelastic models have lots of parameters

- Parameters arranged in a matrix

$$\begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{D} \end{bmatrix}$$

  - 22 Outputs
  - 12 Inputs

- Estimate of parameters for multiple model types

	Rigid longitudinal model	Parameter ID models	Aeroelastic Plant	Full Aeroelastic Model
States	4	6	155	234
Max parameters	416	504	33,807	62,976
Typical parameters	135	270	10,299	14,958

- System order causes many parameters
  - Inputs and outputs also mean a lot of parameters
  - Physical modeling requires more parameters then identifiable from flight

Preflight Flutter Model Tuning

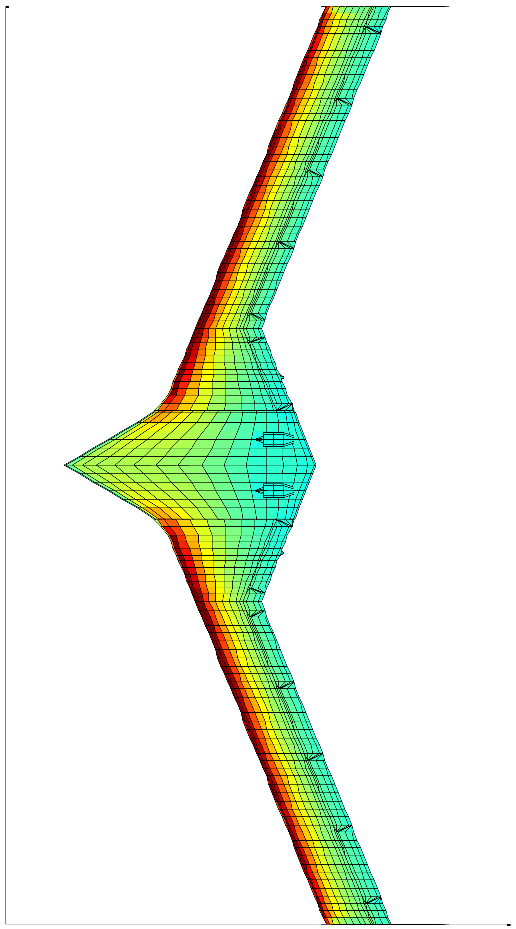
Flutter model uses a lifting surface method
- Similar to vortex lattice
  - potential flow without boundary layer or thickness effects
- Good for unsteady aerodynamics
- Poor for steady coefficients

Refining flutter aerodynamic model
- AIC matrices relate local velocity to pressures

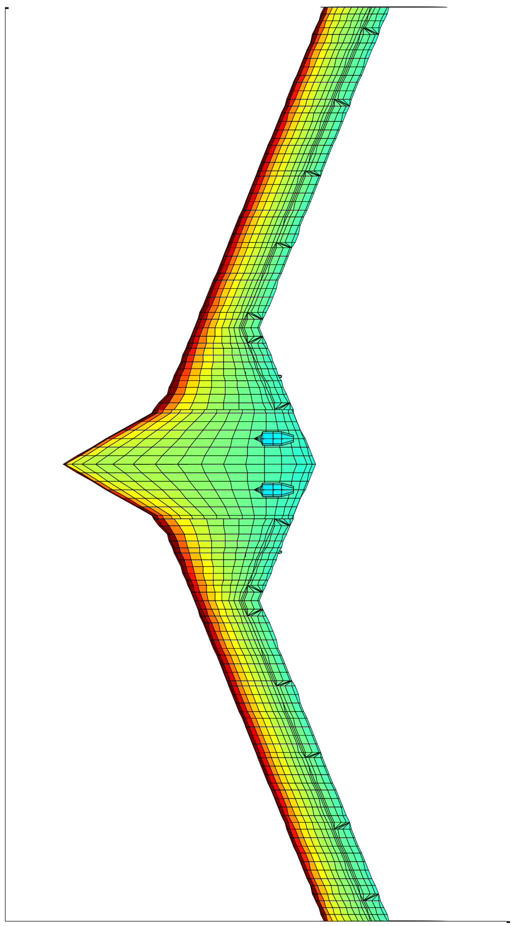
Common techniques exist for refining these matrices
- Tuning to match wind tunnel/CFD results
- Effectively changing the shape to reflect the boundary later and thickness.
  - Downwash correction
- Fairly easy to implement
- Fairly easy to create problems

Currently only matching steady coefficients

STAR-CCM+ ΔC_p



ZAERO ΔC_p



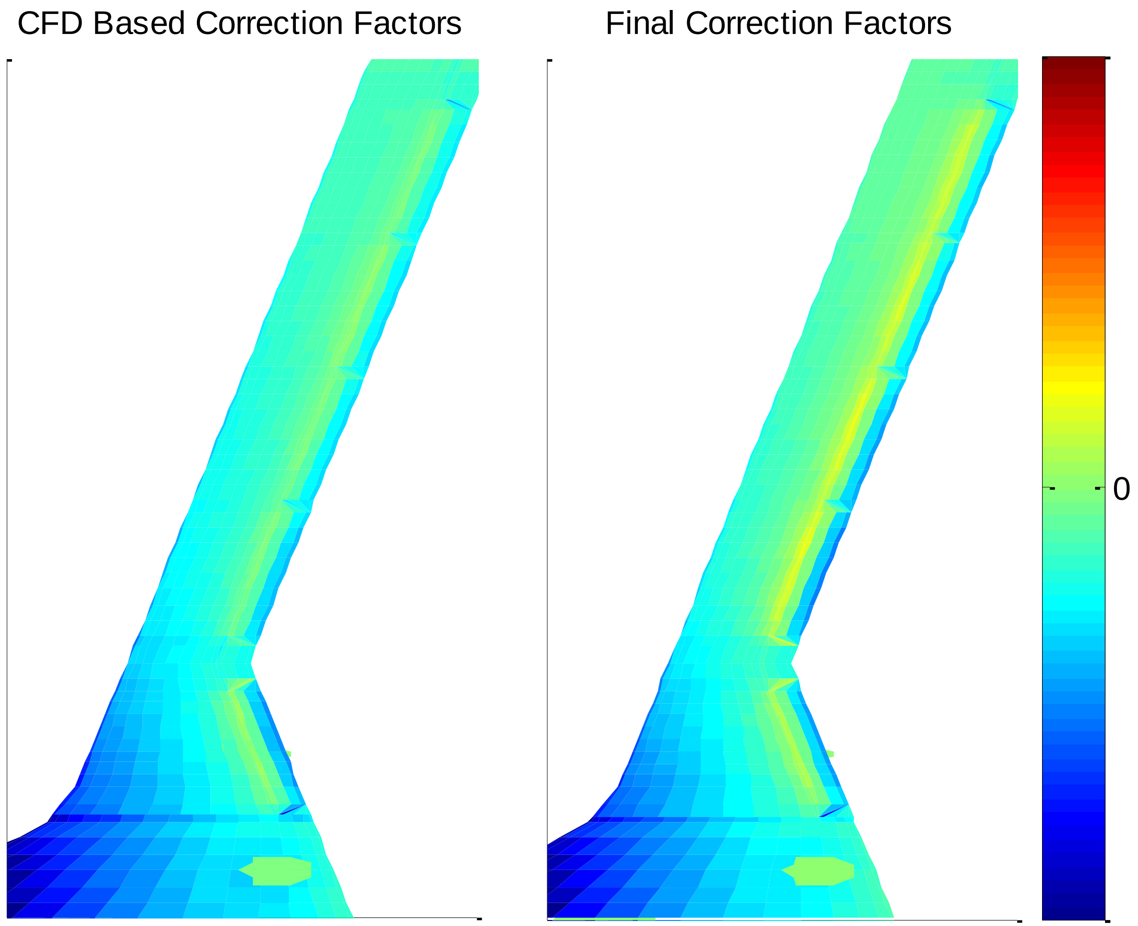
Issues in flutter model tuning

Correction reflects error in relative change in local velocity

CFD/Wind tunnel includes physics not in potential flow models
- Cannot tune to match physics not in the model
- Requires replacement of coefficients

Coefficients may not be consistent
- Matching lift and moment may require unrealistic center of pressure
  - Mostly an issue in control surfaces
- Causes unrealistically large corrections
- Can only match a limited number of coefficients

Smoothness of corrections
- Giesing, Kalman, and Rodden used weighted RMS
  - Limits total variation
  - Large changes between neighbors is possible
- We have implemented smoothness based on difference between neighboring panels



Direct Tuning with Flight Data

Low order PID results have different model structure

- Lower order means the parameters are biased
- Requires an adjustment to parameters

Directly adjusting parameters used in model generation

- No adjustment needed for implementation
- Full envelope correction
- Also applied to generate LOES models

Frequency Domain

- No estimation of states required
- No inclusion of control system needed

Output Error

- Using only accelerometers and strain gauges
- Data directly from flight test instrumentation has more consistent timing

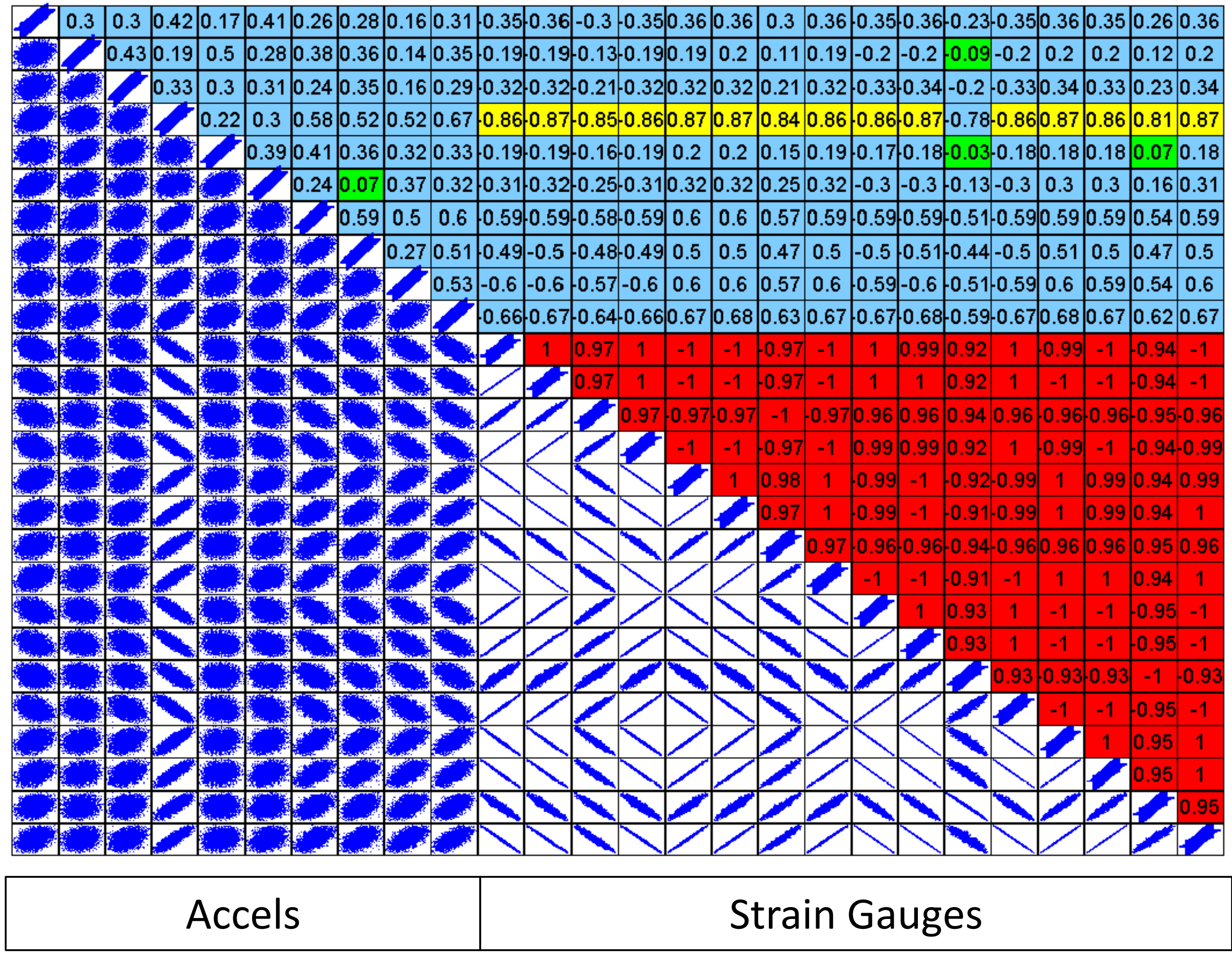
Simplifying the Outputs

Outputs are highly correlated
- Each strain gauge contains essentially the same information
- Turbulence will cause signal errors to be correlated

Principle component analysis (PCA/POD/KLT)
- Combine base on linear relationships
  - Reducing dimension of the outputs
  - Combining outputs to average out the noise
- Similar to generating modes

Reduced rank regression
- PCA applied to outputs

Tested on generating low order models
- Reduces number of parameters fit
- Improves speed (~100x) and accuracy of the fitting



Direct Tuning with Flight Data

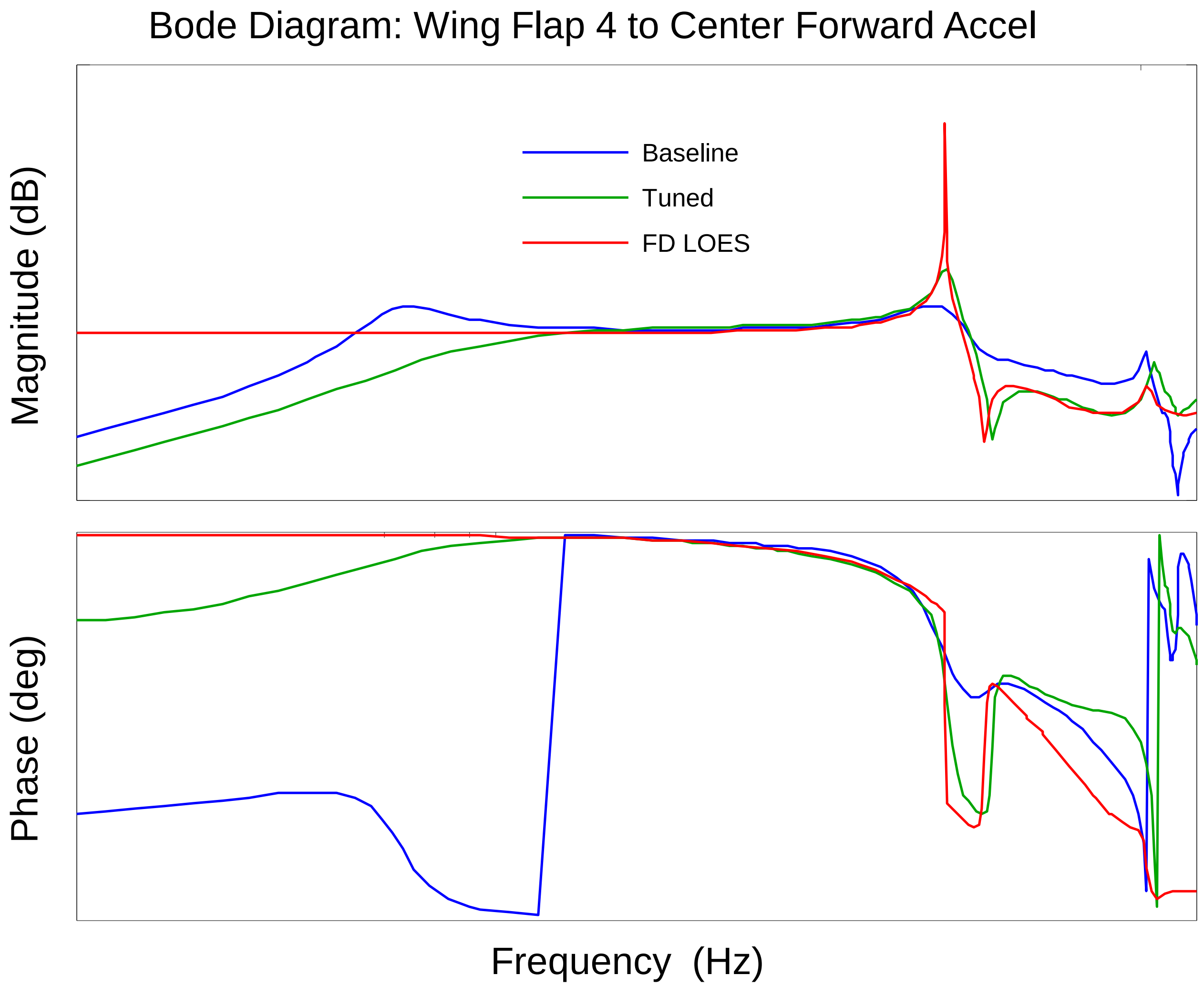
Tuning is improving the fit

Additional improvement is still expected

- Flutter speed is still high
- Unable to get full envelope correction
- Large corrections

Additional parameters may be needed

- Updating 58 parameters
- LOES models have ~200 parameters
- Inertial Parameters
- Structural Parameters
  - Update material properties, rather then frequencies
  - Mode shapes are fixed
  - Output equations are fixed

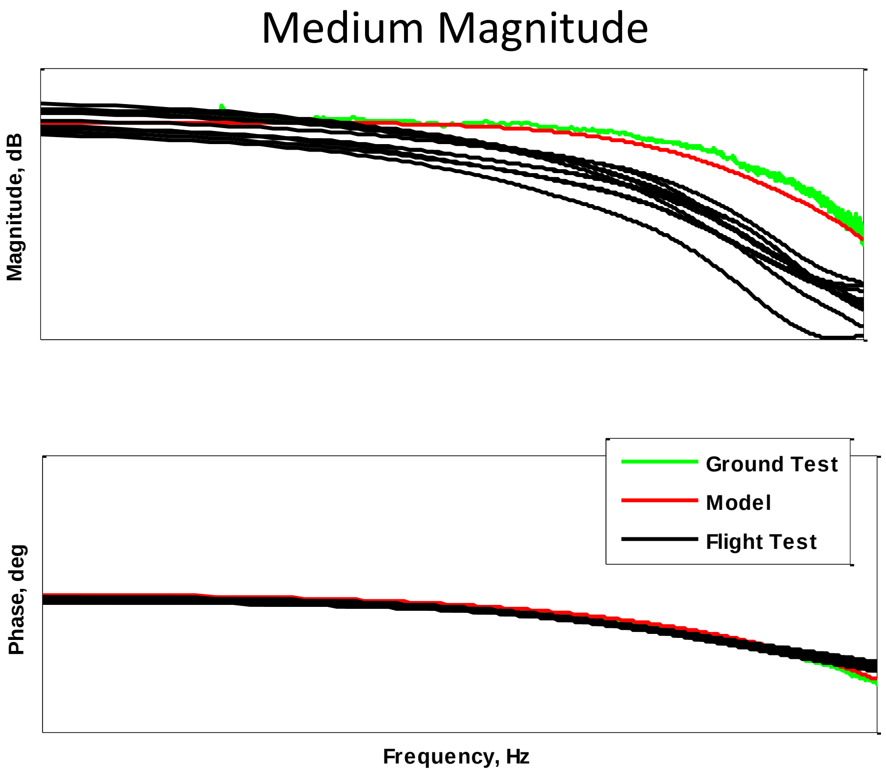


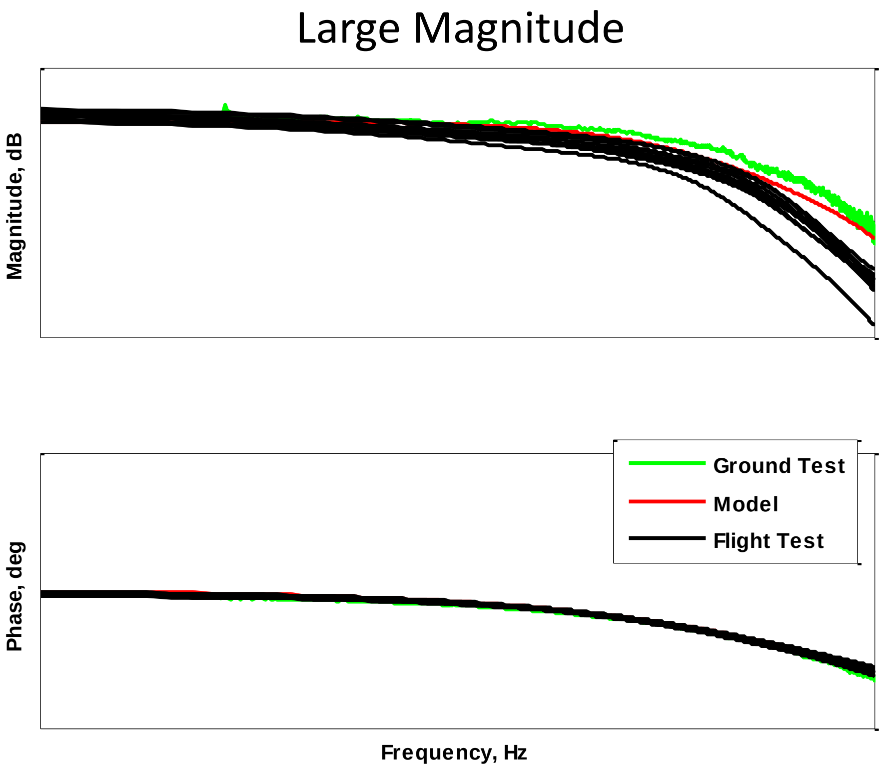
Nonlinearities

ACTUATORS

TAKE-OFF AND LANDING

Effect of Actuator Nonlinearities





- Actuators do not respond to small commands
- Same flight and input (system ID), different magnitudes (x2)
- Same low airspeed, similar fuel weight
- Smaller magnitude shows more variability, and large error relative to ground test

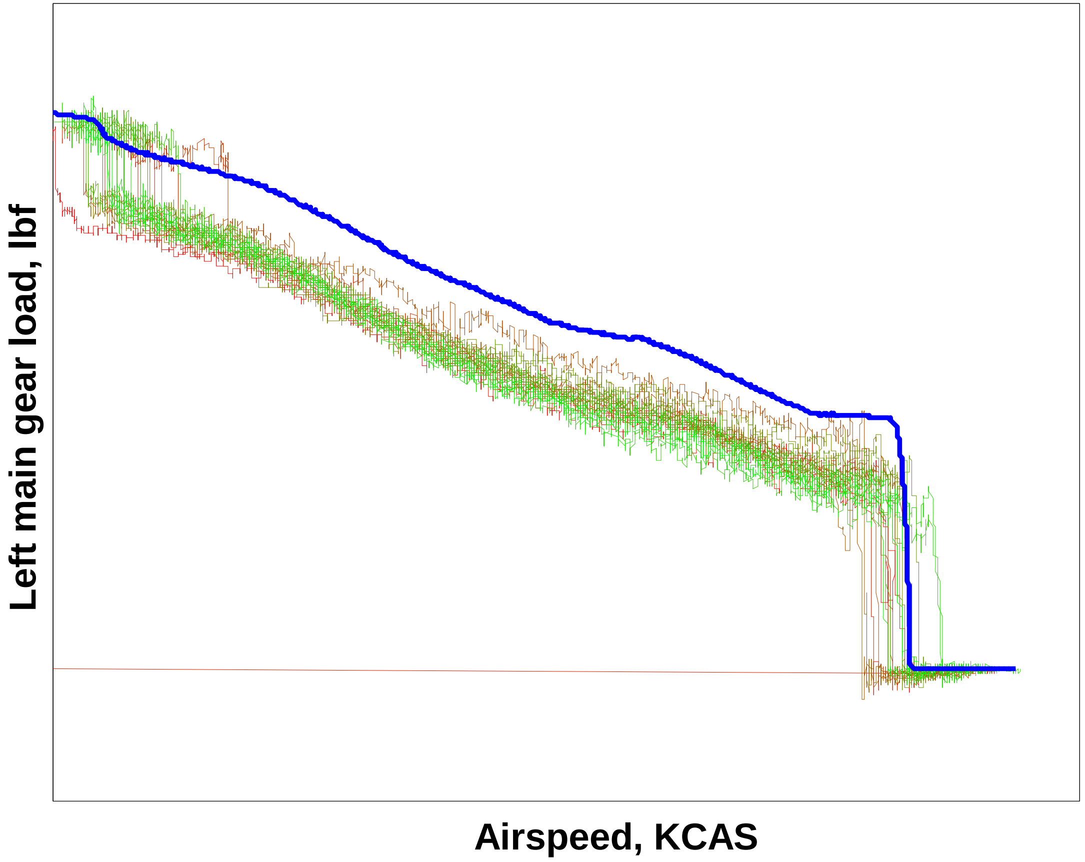
Take-off Simulation

Rapid decrease in main gear loads with increased throttle

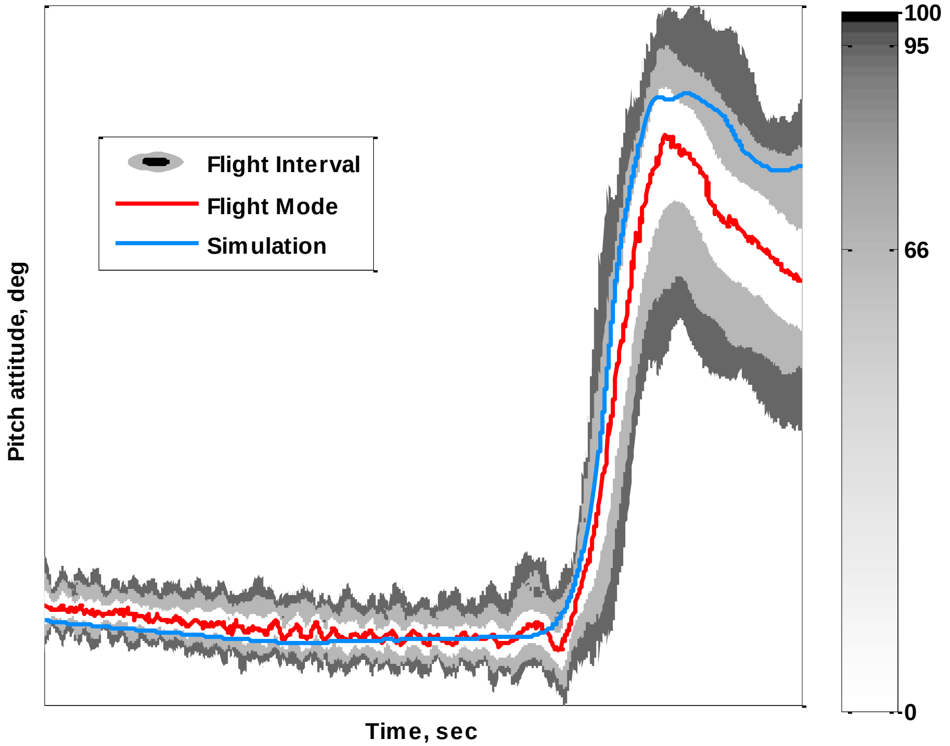
- Not captured in the simulation
- Change in load is ~40% of change in thrust

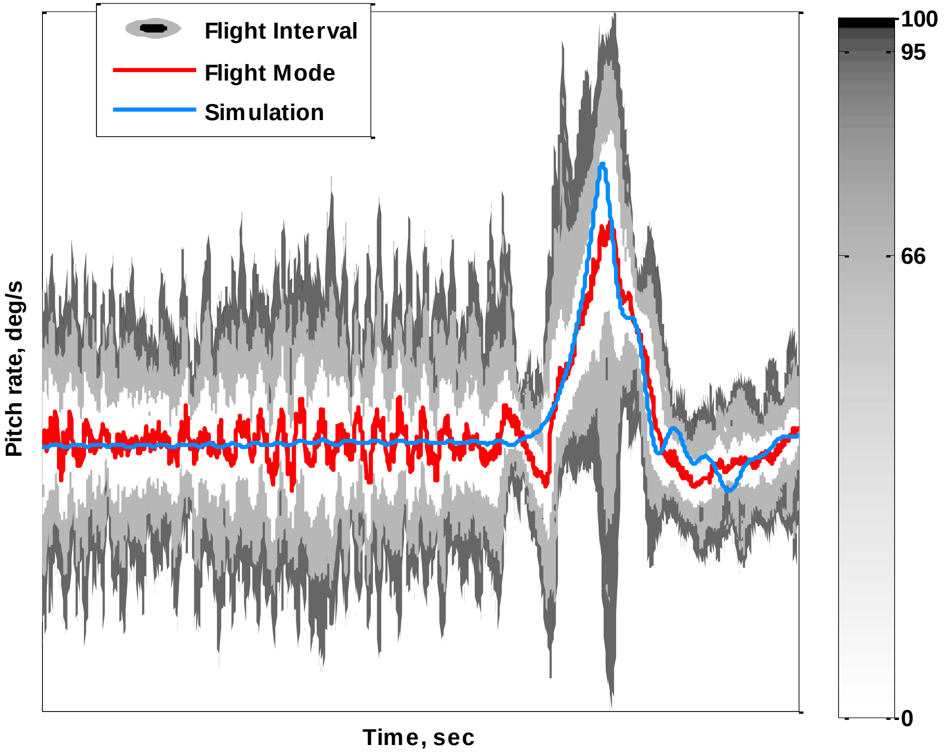
Simulation predicted higher rotation speed

- Higher rotation speed irritated the pilots
- Simulation used in training adjusted ground effect
  - Not physical
  - Small detriment to accuracy of landing dynamics



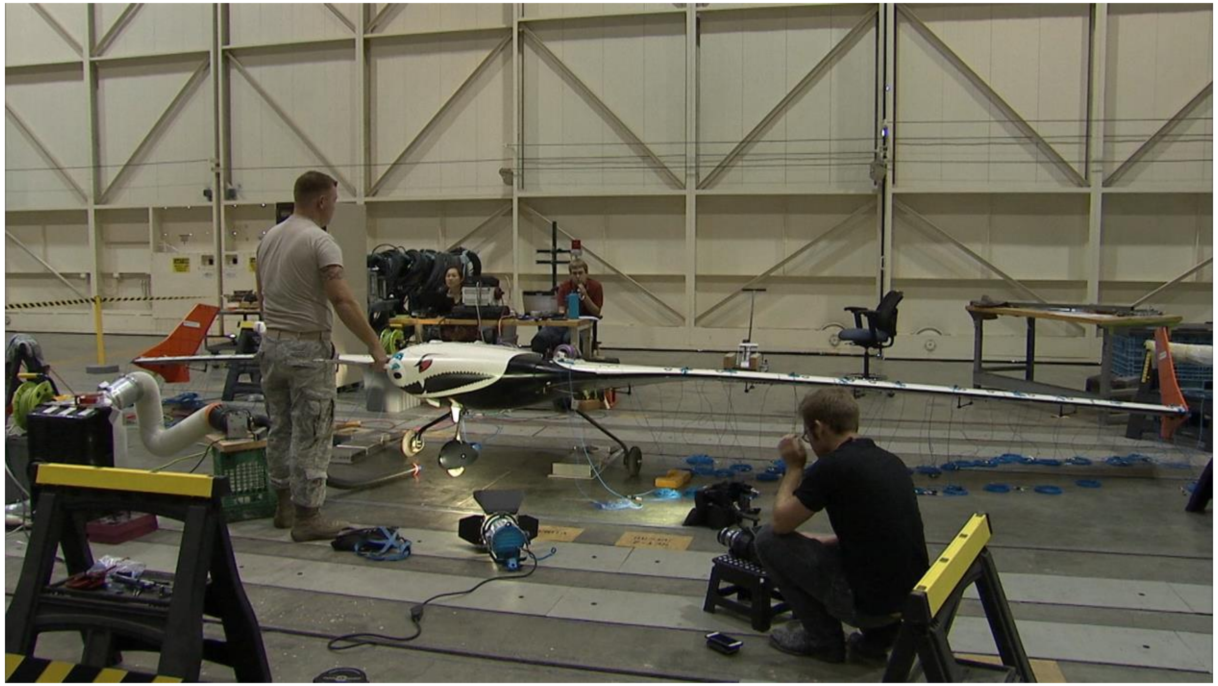
Take-off Simulation





Higher rotation speed causes larger pitch up

Flexibility degrades landing damping



- On touchdown significant energy goes into the wings
  - Wings are very poorly damped
  - Reduces effectiveness of landing gear
- Rigid body simulation did not reliably predict the response
- Out piloted simulation included structural dynamics

Uncertainty and Noise

TURBULENCE

LIMITED KNOWLEDGE (EPISTEMIC)

VARIABILITY (ALEATORIC)

Turbulence

First flex wing flight (flight 9)

- Encountered light to moderate turbulence

Pilot perception

- Had simulated similar levels of turbulence
- Response was more stressful in flight

Structural dynamics

- Added to piloted simulation before flex wing flights
- Effects were not added to nose camera motion

Turbulence model

- Used standard model from loads and handling qualities
  - These primarily excite rigid body motion
- Higher frequency turbulence caused more structural motion

Limited Knowledge (Epistemic Uncertainty)

Uncertainty often viewed as a lack of knowledge

- More testing could improve knowledge and reduce uncertainty
- More testing not always necessary or practical

Unrelated parameter uncertainty

- Large number of parameters
  - Caused unrealistically large uncertainty in output
  - Error in parameters should be related
- Down select parameters based on engineering judgement
  - Missed parameters that are important

Mu-analysis was very appealing

- Computational cost was excessive
  - To many parameters to examine
- Frequency of parameter occurrence
  - Mass parameters and air density effect many parameters
- LFT format was still useful for Monte Carlo

Flight models show what output uncertainty should be

- Models were sufficient for controller design, once the uncertainty was known

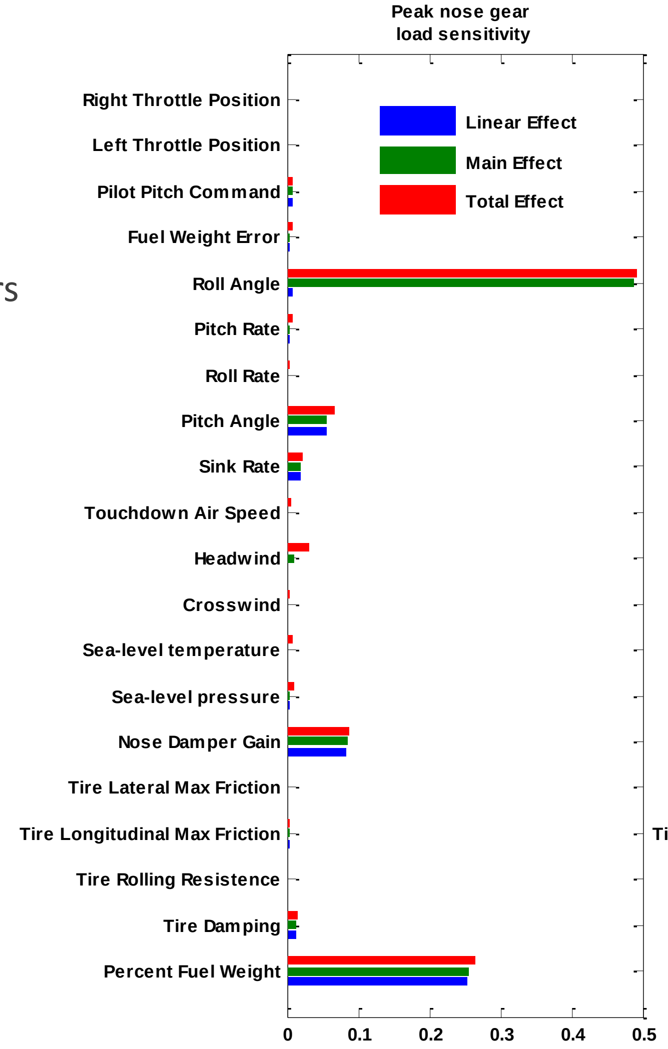
Variability (Aleatoric Uncertainty)

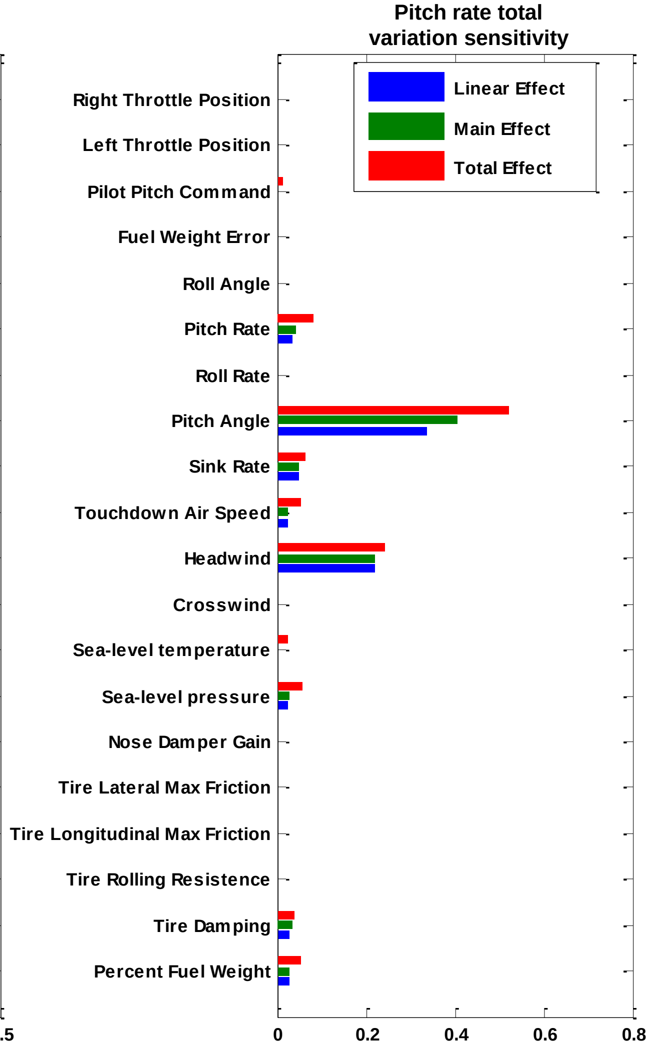
Landing Sensitivity Analysis
- Some uncertainty is inherent, and cannot be reduced

Examined sensitivity of the response to parameters
- To many parameter combinations to consider
- Needed to understand interactions between parameters
- For 26 parameters, $2^{26} \approx 10^8$ possibilities
  - >2 years for a 1 second simulation

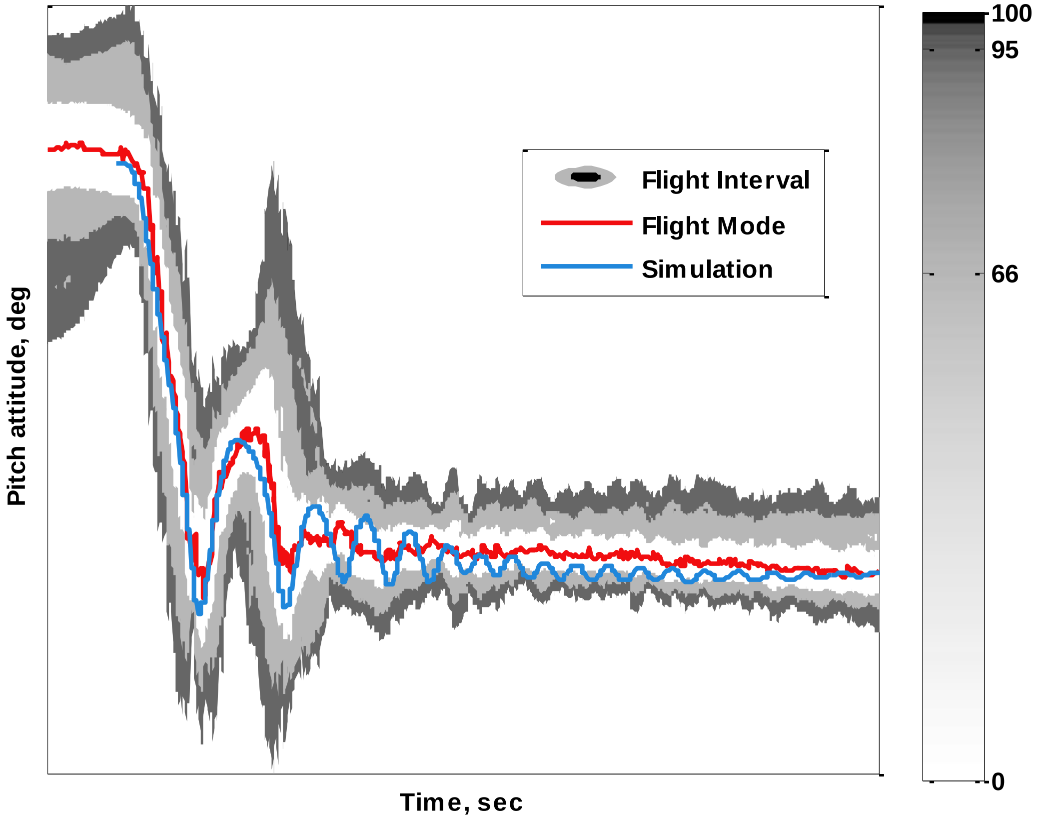
Monte Carlo/Polynomial chaos expansion
- Generate surrogate model
- Polynomials orthogonal with respect to parameter probability distribution

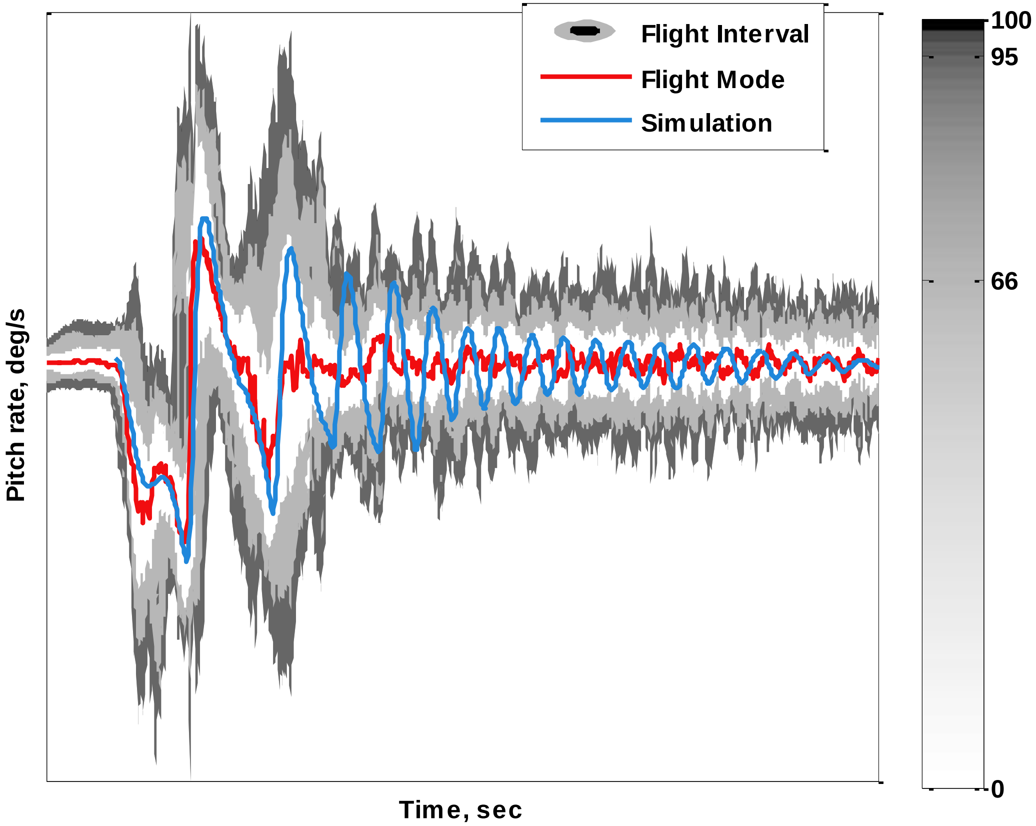
Used multiple types of sensitivity
- Linear effect: traditional linear sensitivity
- Main effect: direct nonlinear effect
- Total effect: Includes interaction between parameters





Landing Dynamics



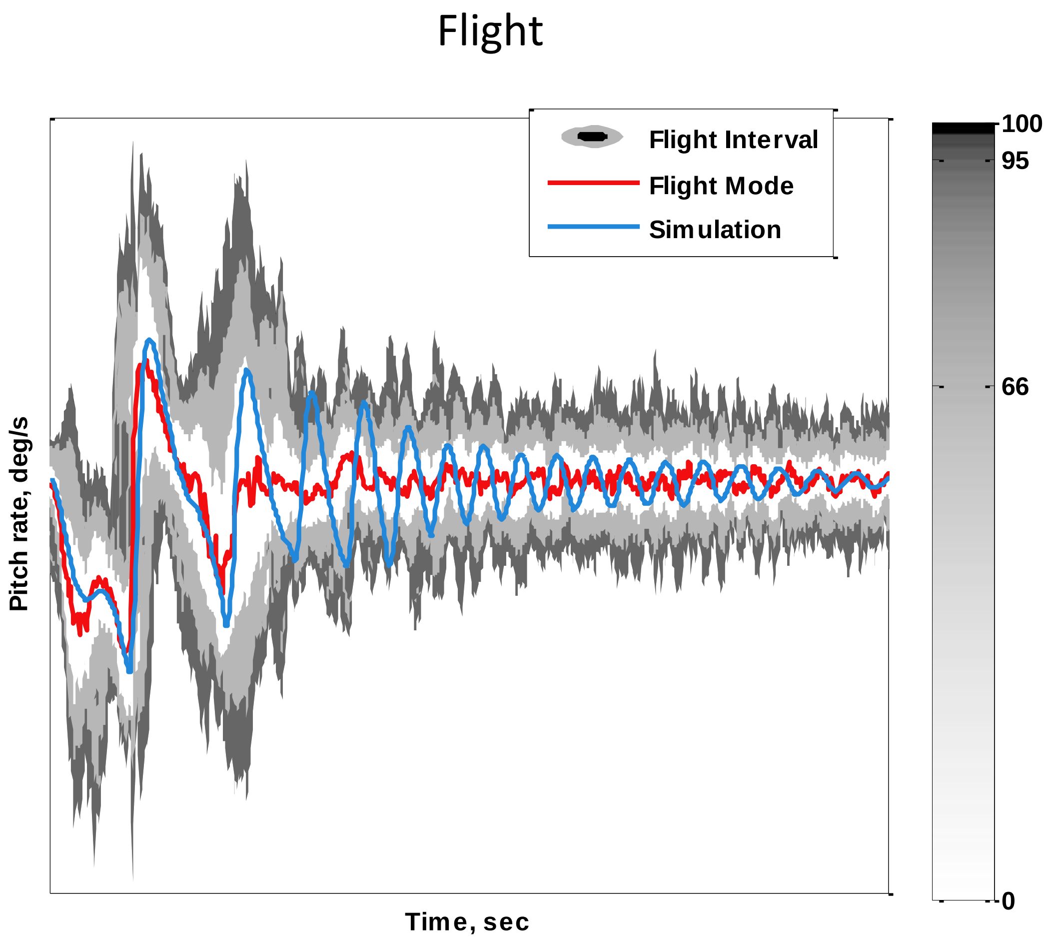


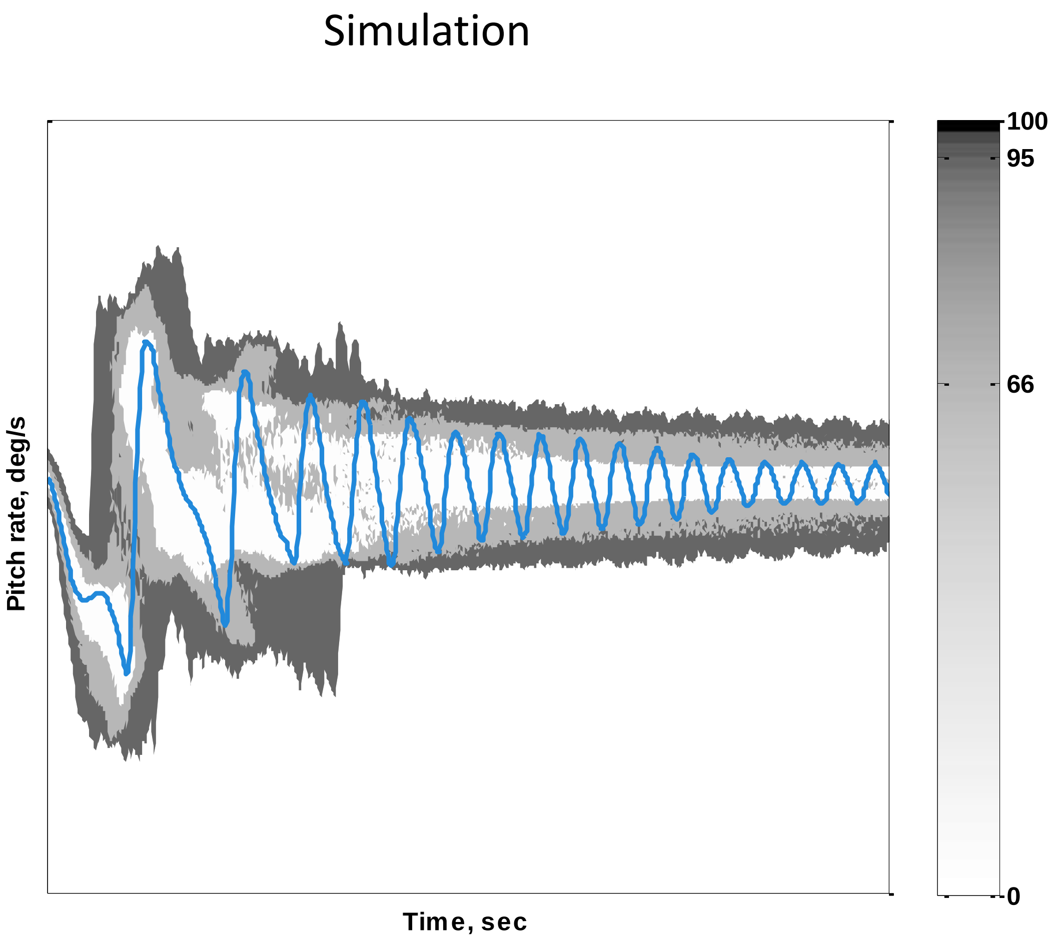
Simulation is capturing initial dynamics

- Nonlinearity of ground contact makes comparison difficult

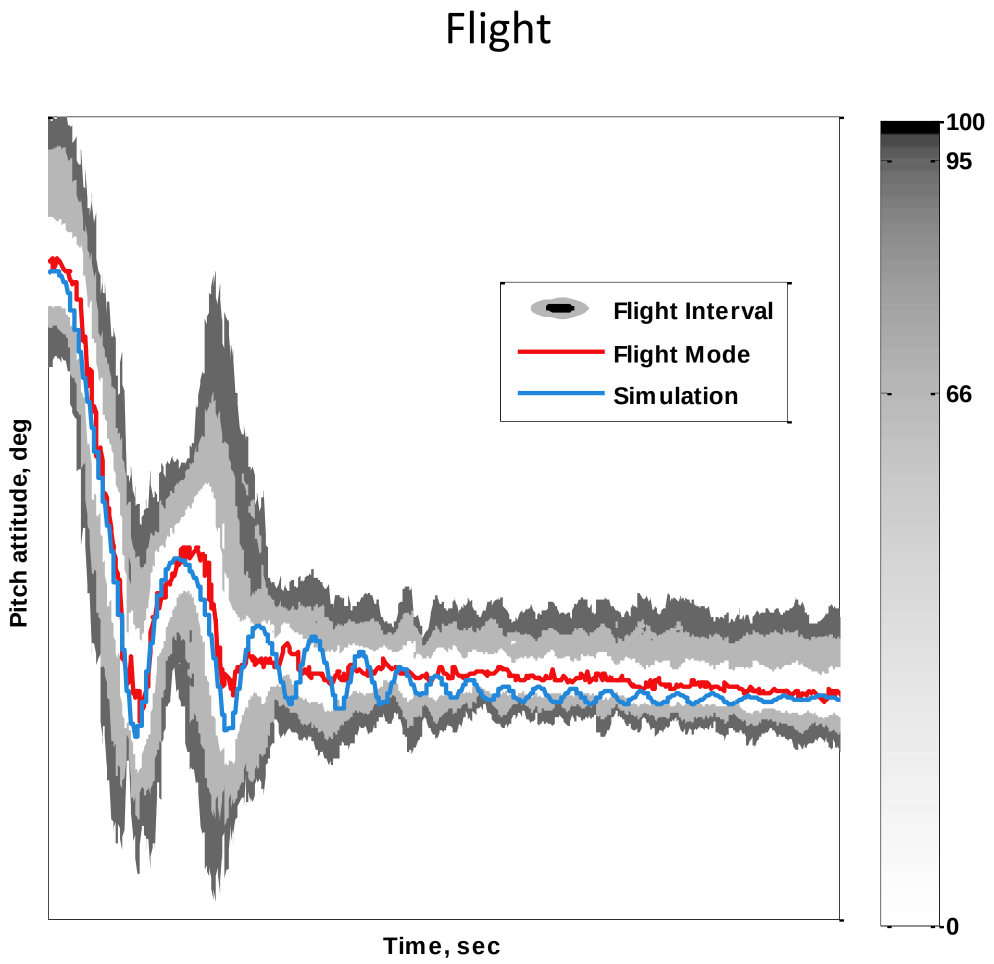
Having a piloted simulation allowed for the development of an effective landing technique.

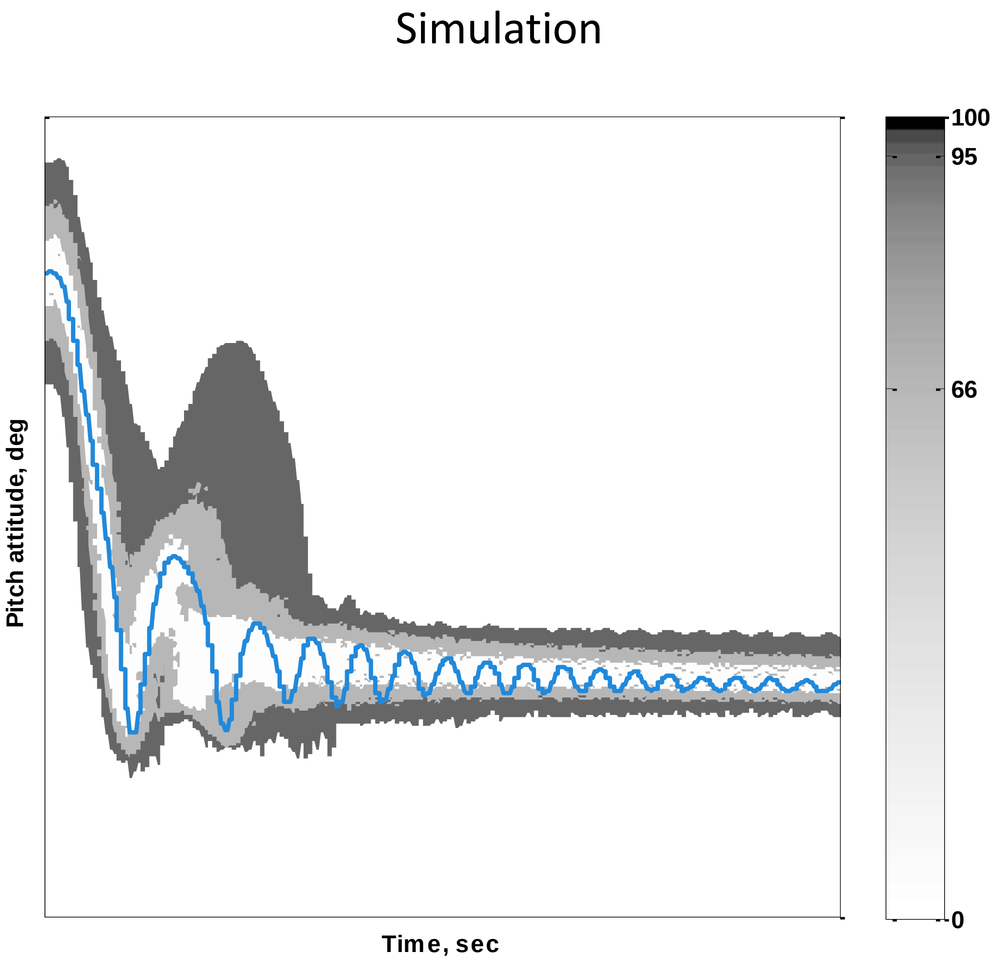
Landing Monte Carlo





Landing Monte Carlo





Conclusions

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Have generated models of reasonable accuracy

- Used to design control system past flutter
- Used to address and validate takeoff and landing issues
- Challenges do still remain

Developed tools and methods for ASE challenges

- Unstable closed loop system
- Complex dynamics
- Nonlinear behavior
- Uncertainty