Nonlinear Aerodynamics Modeling Using Fuzzy Logic

Jay Brandon

Eugene Morelli

Outline

- Background
- Innovations
- Fuzzy Logic Technical Approach
- Flight Test Data
- Result Examples
- Next Steps
- Closing Remarks

Flight Dynamics Analysis Process

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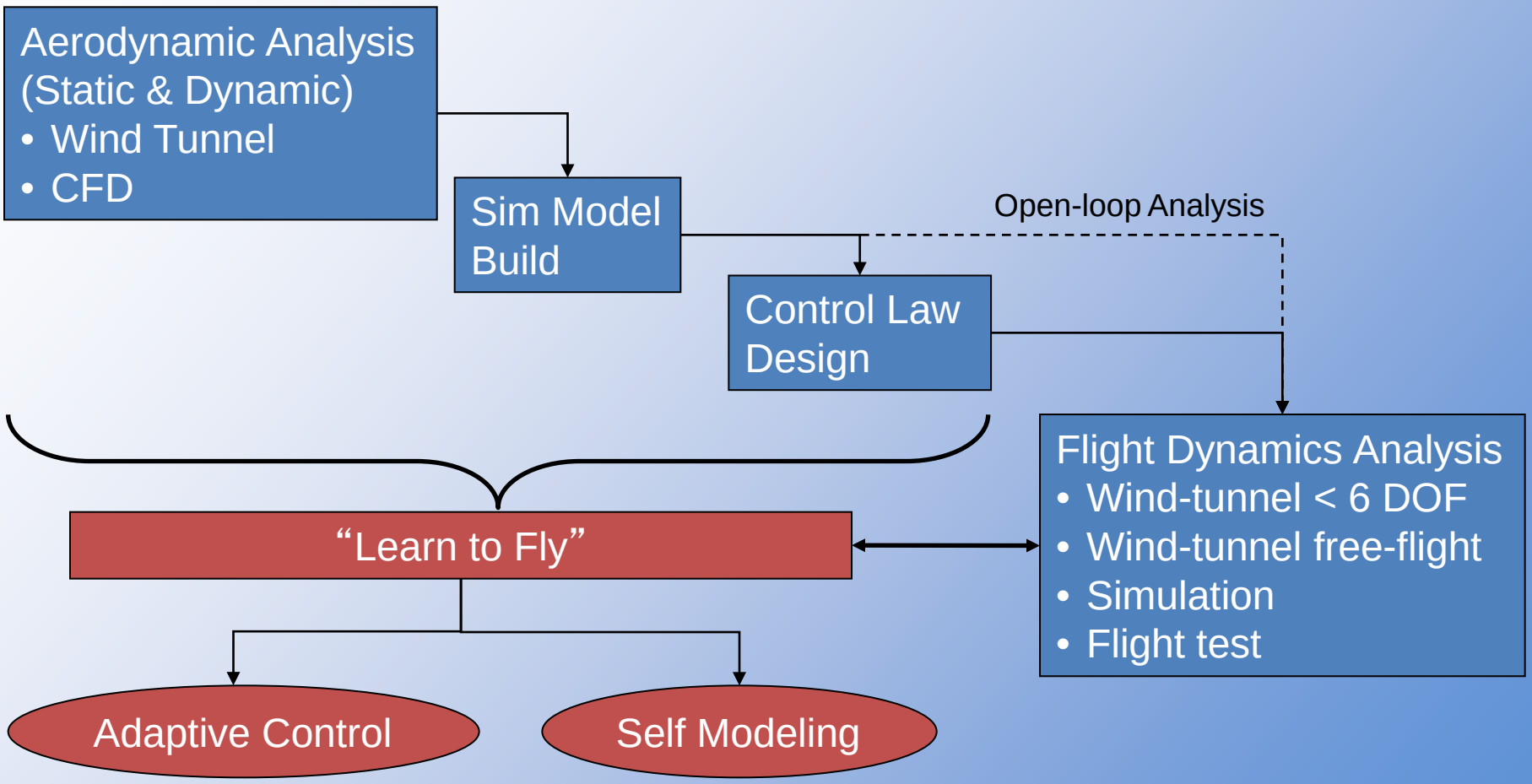

Aerodynamic Models

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- Aerodynamic Models
  - Model of physics so that design and analysis can be undertaken
  - Based on data
    - CFD, Wind tunnel, Flight, …
  - Linear representations
    - $C_x = C_{x_0} + C_{x_\alpha}\alpha + C_{x_\beta}\beta + C_{x_\delta}\delta + \ldots$
    - $C_x|_{(\alpha=x)} = C_{x_0}|_{(\alpha=x)} + C_{x_\alpha}|_{(\alpha=x)}\Delta\alpha + C_{x_\beta}|_{(\alpha=x)}\Delta\beta + C_{x_\delta}|_{(\alpha=x)}\Delta\delta + \ldots$
  - Nonlinear representations
    - $C_x = f(\alpha, \beta, \delta, \ldots)$
- System Identification
  - Determination of structure of model
- Parameter Identification
  - Determination of parameter values within the structure of the model

Phase I Innovations

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- Nonlinear Aerodynamic System Identification
  - No model structure specification required
  - Large flight envelope with single model
- Flight Test Techniques for Rich Data Content
  - Multi-axes inputs over large range of flight conditions
  - Piloted adaptation of similar orthogonal input techniques
- Blending of Data from Different Sources
  - Ship research data acquisition system
  - iPad internal sensors for inertial data and GPS

Fuzzy Logic System ID

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- Modeling Challenges Due to Nonlinear Effects
  - Separated flow
  - Large amplitude motion of vehicle or control effectors
  - Interactions
  - Unsteady, time-dependent aerodynamics
- Fuzzy Modeling Characteristics
  - No a-priori or interactive model definition required
  - Fuzzy cells constructed to identify relationships between input data and output data
  - Single model across wide range of state variable variations
- Relatively New Application for Fuzzy Logic
  - Widely used in controls applications
    - Good for use in areas where there is a lack of quantitative data regarding input-output relations
  - Synergistic with other parameter ID technologies

Fuzzy Logic Approaches

- Fuzzy Sets
  - Membership functions
  - Weighting factors
  - If-then rules
- Similar to human decision-making process
- Predicted outputs tend to be piece-wise continuous
- Used extensively in controls applications

- Fuzzy Internal Functions
  - Membership functions
  - Internal functions
  - Fuzzy cells
- Multiple internal functions create the "fuzziness"
- Predicted outputs are smooth

Fuzzy System ID Process

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Pre-Processing
- Force & Moment
- Data Consistency
- Corrections

Select Regression Variables
- Normalize
- Partition
  - Training
  - Testing

[α, β, δ, ω, M, …]

Compute MF's

Calculate Internal Function Coefficients for All Fuzzy Cells

$$P^i = p_0^i + p_1^i x_1 + \ldots + p_k^i x_k$$

$$SSE = \sum_{j=1}^{m} \left(\hat{y}_j - y_j\right)^2$$

$$\hat{y}_j = \frac{\sum_{i=1}^{n} \left[A_1^i(x_{1,j}) A_2^i(x_{2,j}) \ldots A_k^i(x_{k,j})\right] P^i}{\sum_{i=1}^{n} \left[A_1^i(x_{1,j}) A_2^i(x_{2,j}) \ldots A_k^i(x_{k,j})\right]}$$

$$R_{trn}^2 > R_{\text{min Required}}^2$$

$$R_{test}^2 > R_{test}^2(Ns+1) > R_{test}^2(Ns+2)$$

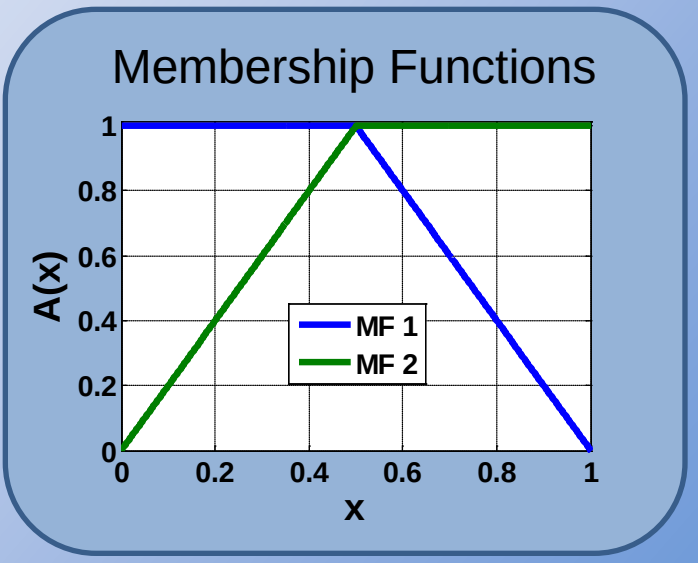
Evaluate Fit : OK?

No

Yes

Calculate Model (with all data)

Stop



Flight Test Data

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- Large flight envelope
- Well instrumented
  - α/β on boom
  - Inertial and controls
  - TM real-time data support

Portable “Data Systems”

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- Nx, Ny, Nz
- p, q, r
- Course, Speed, Altitude
- Attitude Angle Estimates

Blending Example

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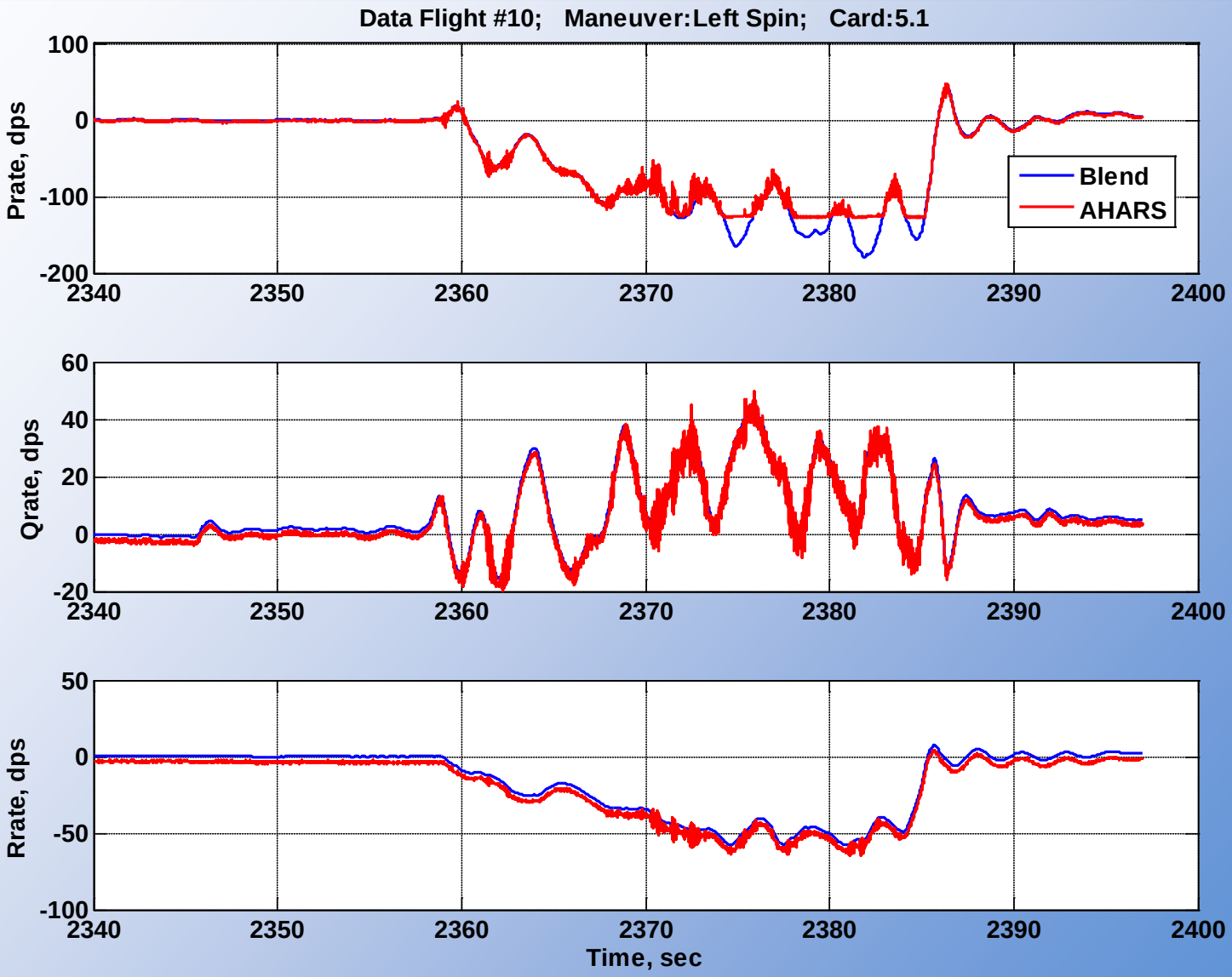

Maneuver Design

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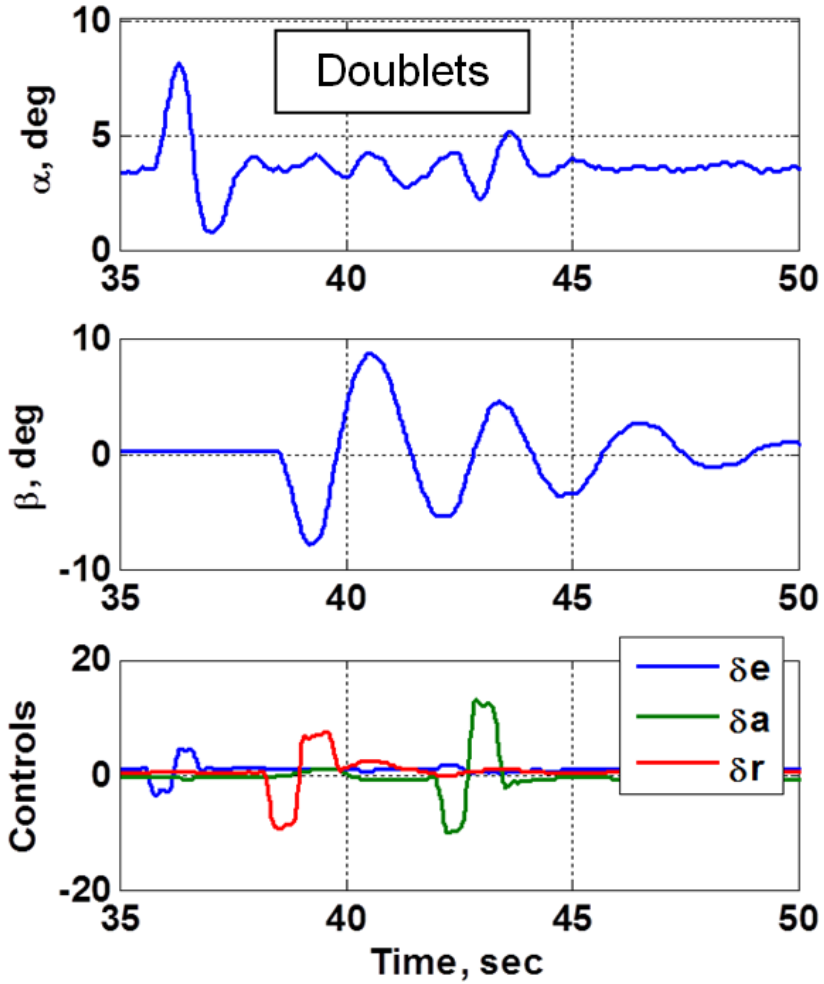

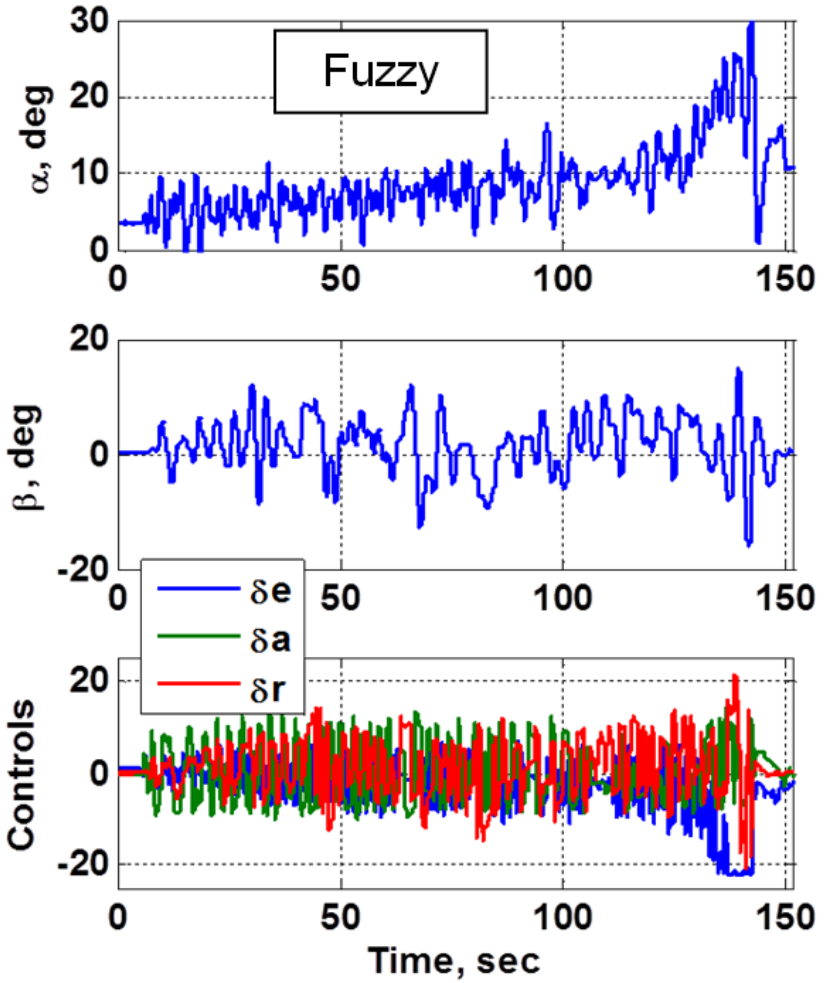

Fuzzy Decel Video (DF9C4)

Parameter Map Examples

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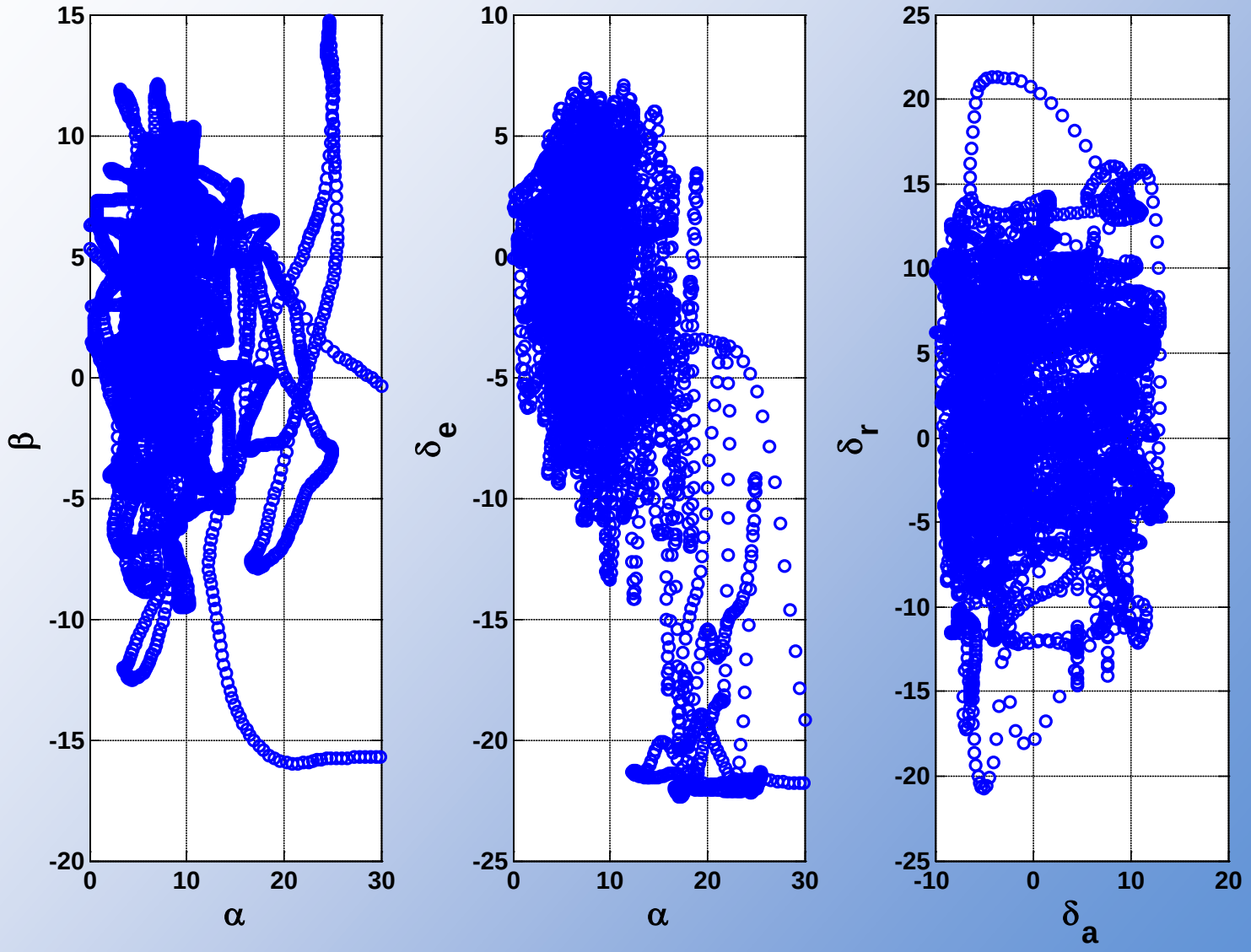

Fuzzy Model Fit

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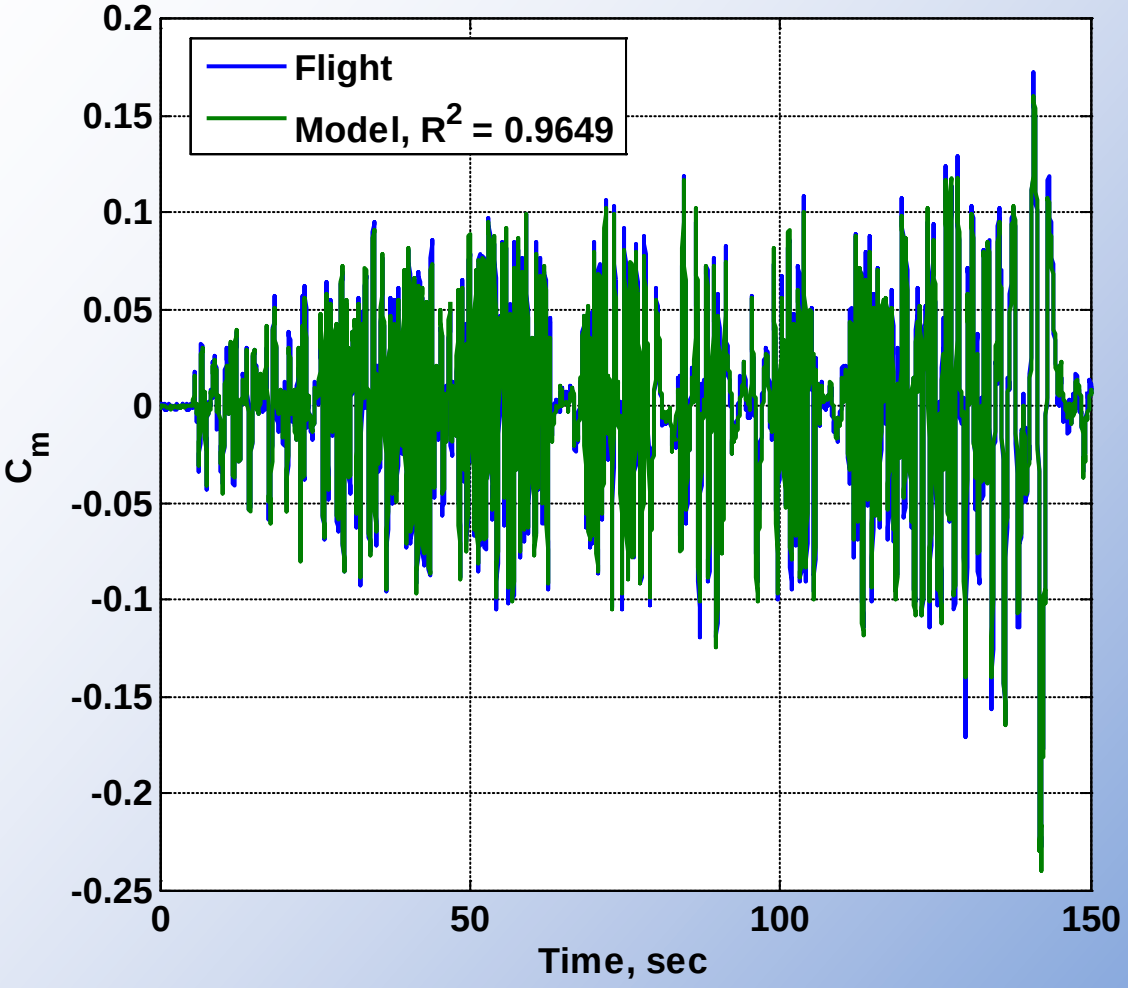

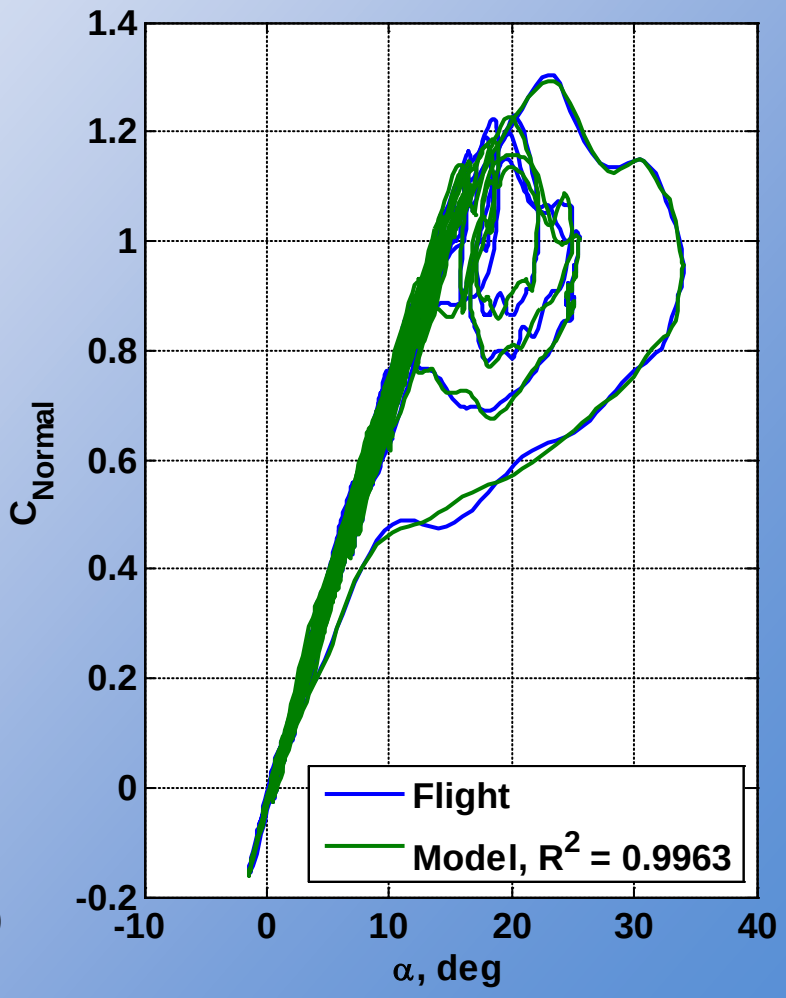

Linearized Model Results

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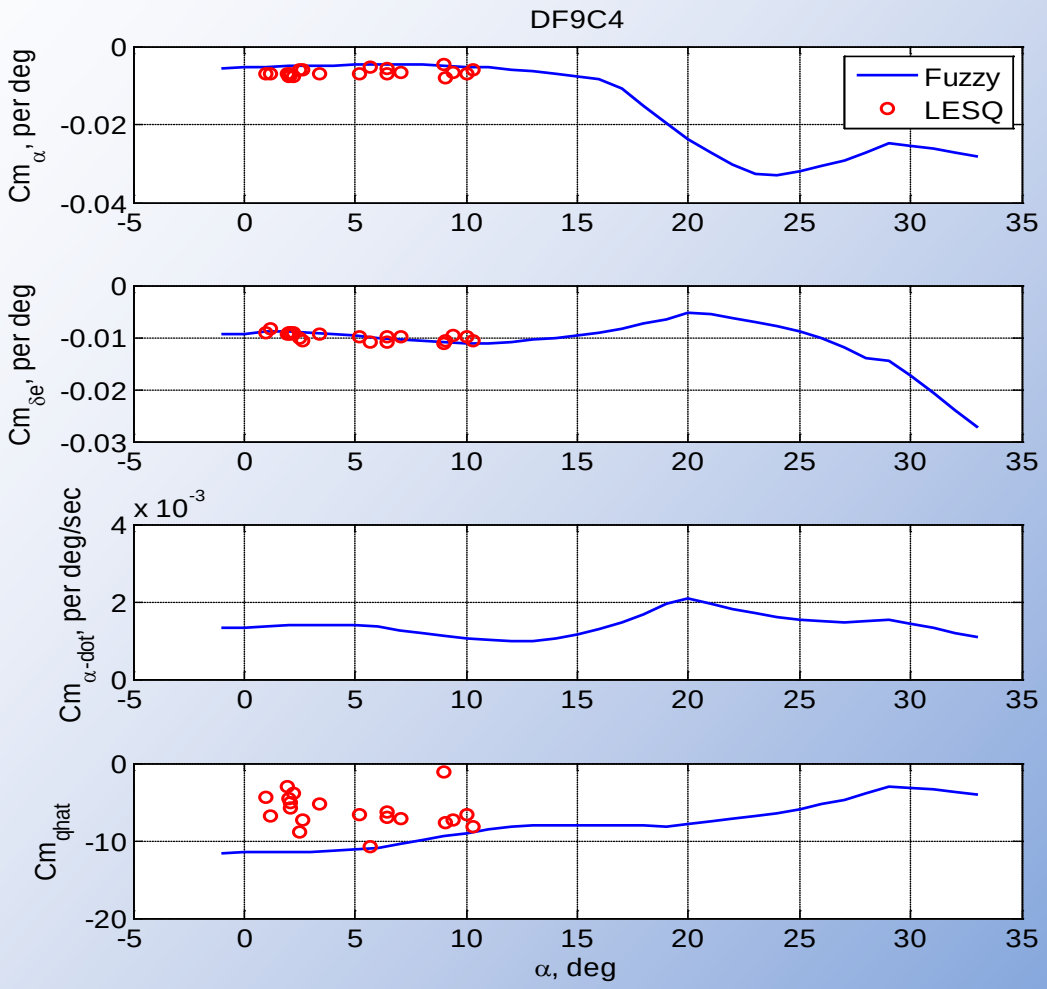

- Large envelope model with one maneuver
- Includes post-stall stability
- Correlates well with traditional maneuver and analysis for static stability
- Very test-efficient

Distribution of Results

- Briefings
  - RD
  - FRSD
  - SFW (Mike Rogers – results kicked off simulation study)
  - Navy P-8 team
  - Test Pilot School Briefing
- Publications
  - Proposed Paper, SETP conference in September, 2012
  - AIAA papers and journals and NASA reports as results are analyzed
- Research
  - Applications in simulation and in wind tunnel testing

Next Steps – Phase II Proposal

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- Refine fuzzy logic system identification algorithms
  - Fuzzy cell filtering
  - Error bounds calculations
- Develop real-time maneuver input guidance algorithms and displays
  - Guidance for maneuver inputs
  - Ensure that required data actually obtained over envelope of interest
  - Ensure that data is of sufficient richness to result in model of desired fidelity
- Improved Airplane Instrumentation
  - Real-time streaming to cockpit
  - Engine parameters
  - Repairs and calibrations
- Advance the processes to provide results in near real time
  - Verify / validate model inflight and obtain more data if needed
  - Develop preliminary aerodynamic model of envelope of interest before landing

Closing Remarks

- Results from Phase I
  - Potential for substantial savings in test time and cost
  - Rapidly available and high fidelity models can improve flight safety
- Phase II Project Outcomes
  - Assurance of data richness and content
  - Aero models available onboard airplane near realtime
  - Model validation inflight
  - Enabler for self-learning and autonomous health monitoring vehicles