System Identification Methods for Aerodynamic Modeling and Validation using Flight Data

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Outline

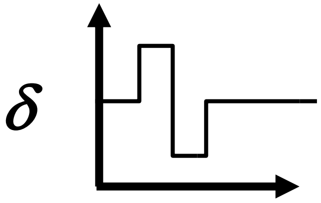
- Overview of Aircraft System Identification
- Multi-Axis Optimized Maneuver Design
- Demonstration Using SIDPAC Software
- Applications
- Concluding Remarks

Aircraft System Identification

System Identification **is the process of building mathematical models for physical systems based on imperfect observations or measurements**

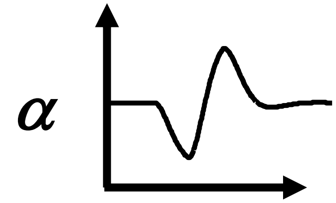
If the physical system is an aircraft, then this activity is called *aircraft system identification*

Problems In Dynamics



Input, *u*

System, *S*



Output, *z*

Simulation: **Given *S* and *u*, find *z***

Control: **Given *S* and *z*, find *u***

Identification: **Given *u* and *z*, find *S***

Aircraft System Identification

$$m\dot{V} + \omega \times mV = F_{Aero} + F_{Thrust} + F_{Gravity} \qquad \left(ma = \sum F\right)$$

$$I\dot{\omega} + \omega \times I\omega = M_{Aero} + M_{Thrust} \qquad \left(I\dot{\omega} = \sum M\right)$$

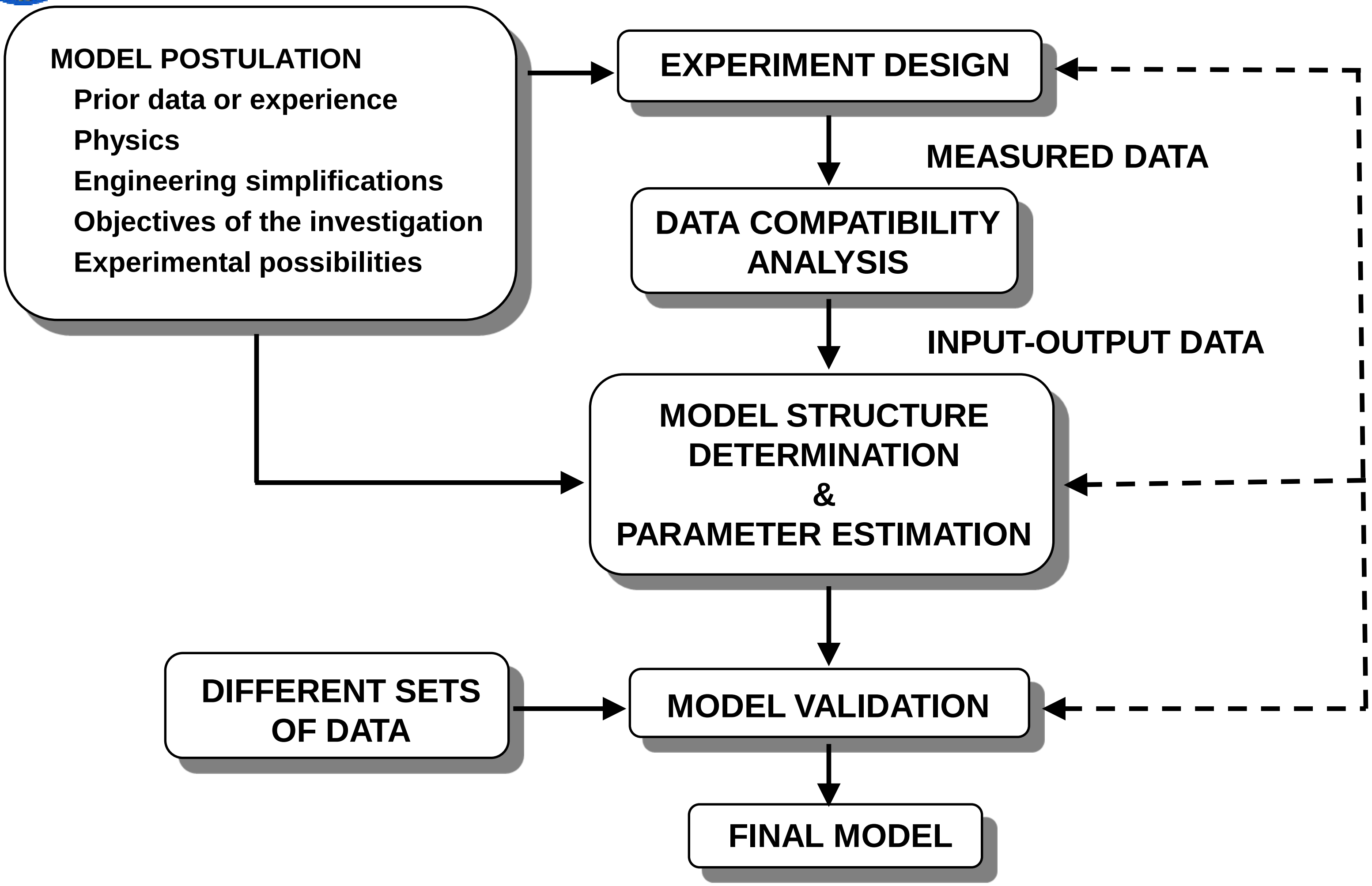
***Typical aircraft system identification problem*:**

From measurements of the inputs and outputs, determine mathematical model forms for F_{Aero} and M_{Aero}, then estimate the unknown parameters in those models

Unknown model parameters

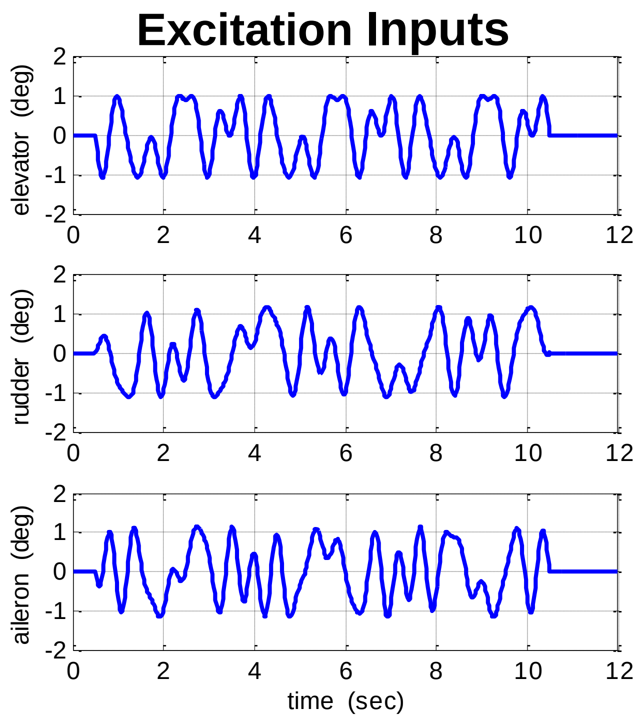
Example: $M = M_o + M_\alpha \alpha + M_q q + M_\delta \delta$

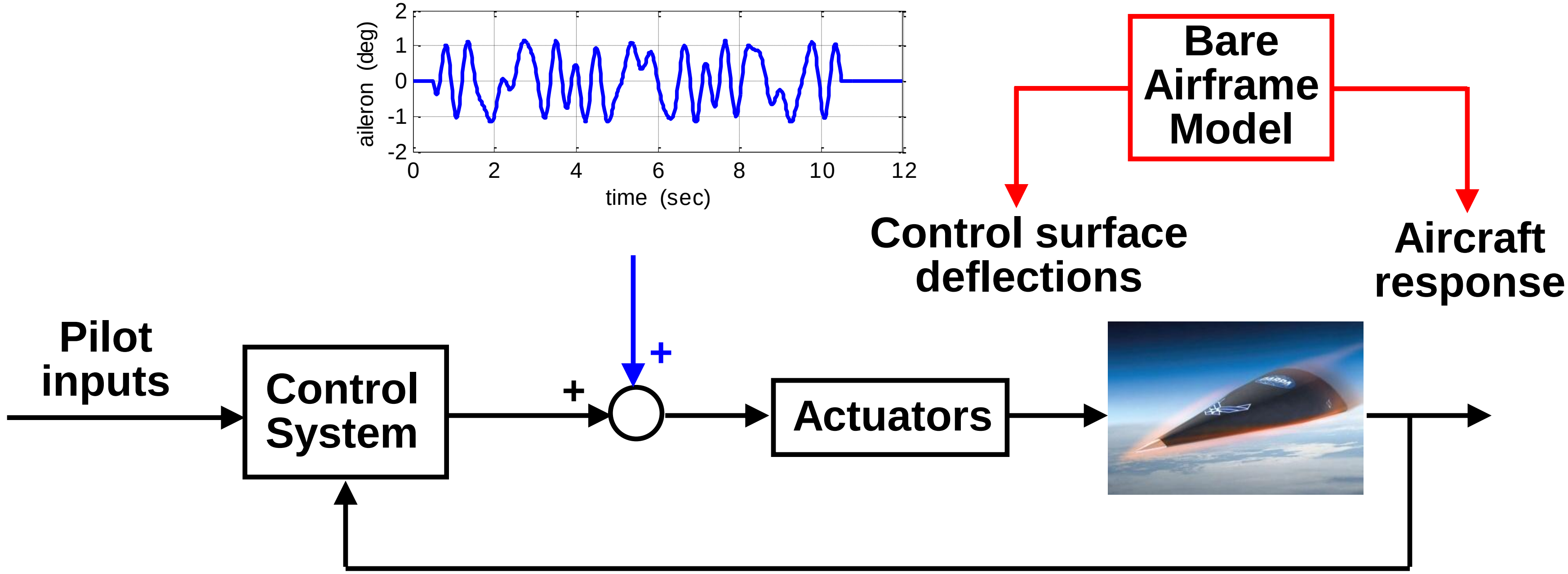
Aircraft System Identification



Note that information embodied in a model is either assumed or derived from measurements

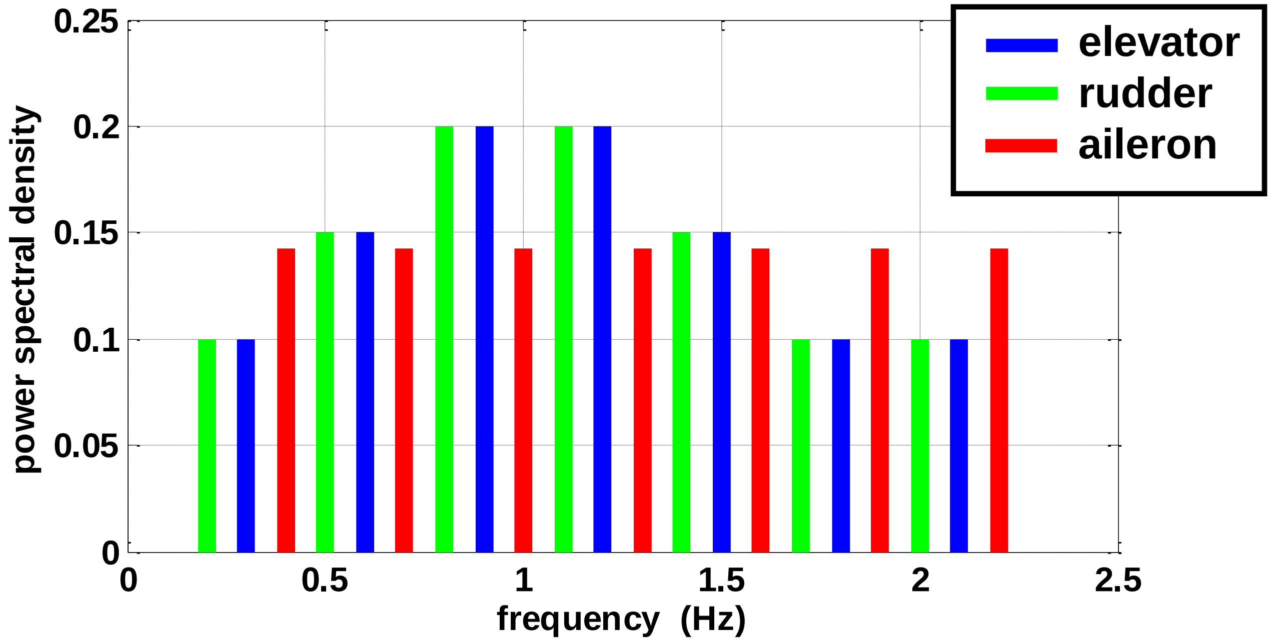
Flight Test Technique





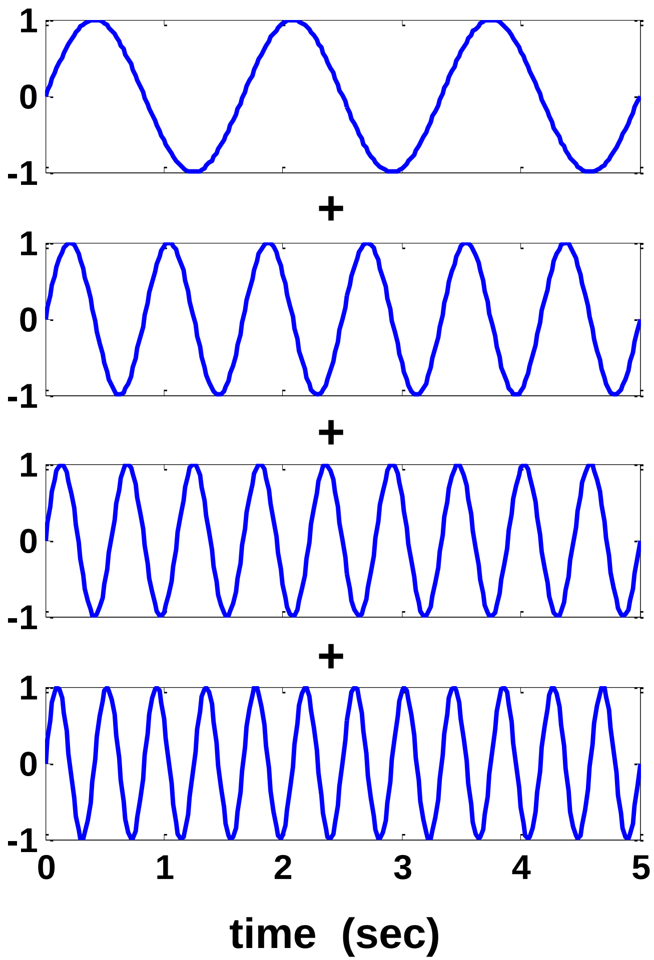
Orthogonal Optimized Multi-Input Design

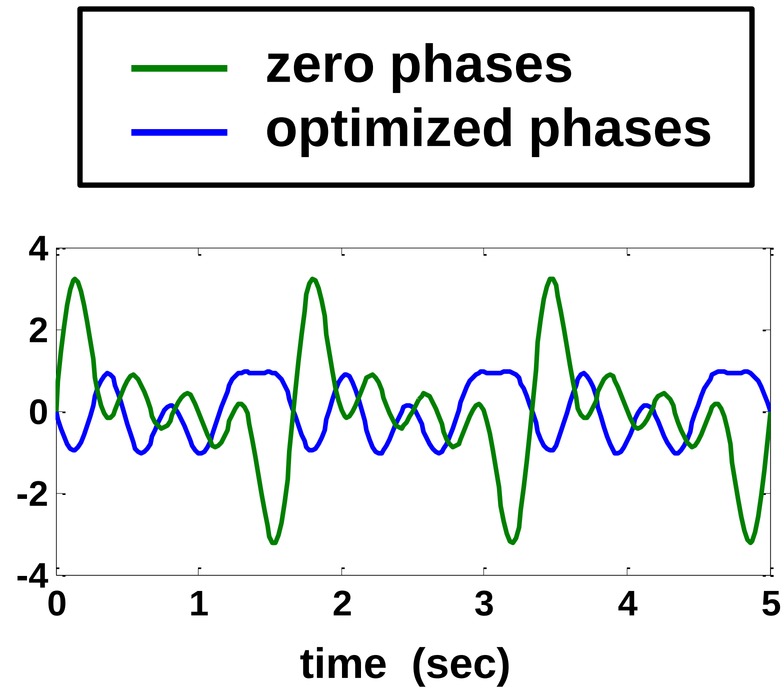
$$u = \sum_{k \in \{1,2,\ldots,M\}} A_k \sin\left(\frac{2\pi k t}{T} + \phi_k\right)$$



Phases ϕ_k **optimized for minimum** $RPF(u) = \dfrac{[max(u) - min(u)]}{2\sqrt{2}\, rms(u)}$

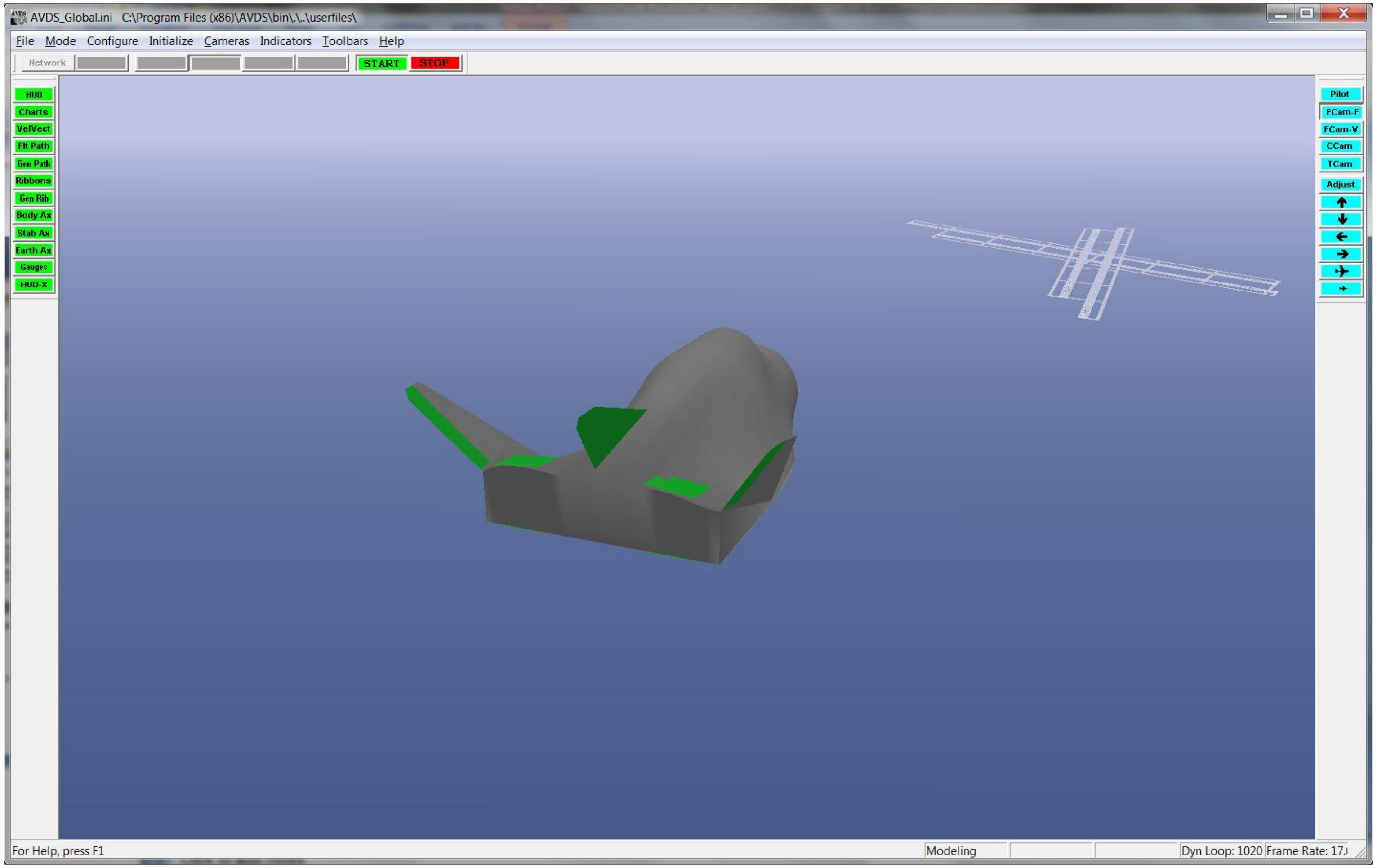
Multi-Sine Phase Optimization





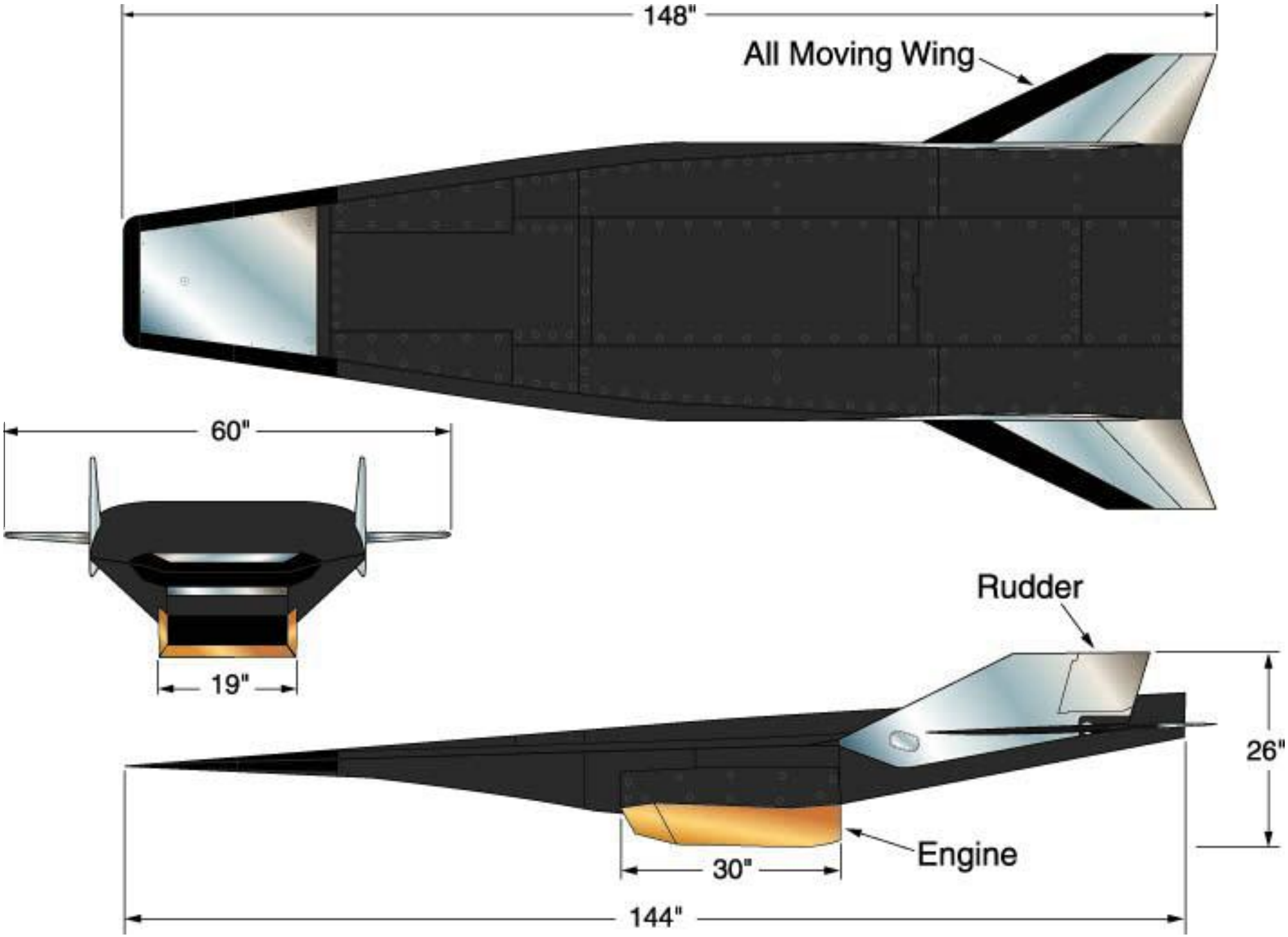
SIDPAC Demonstration

HL-20 Approach

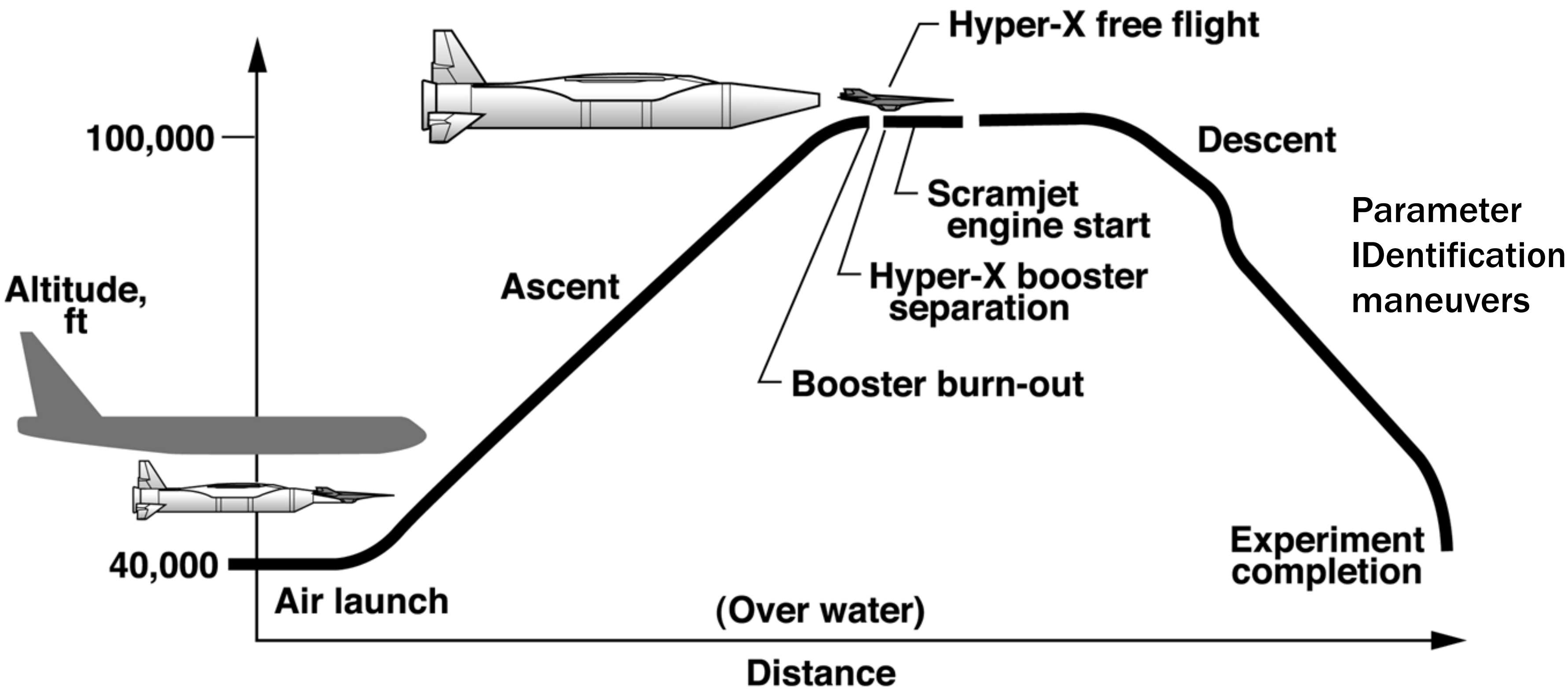


Hyper-X Launch

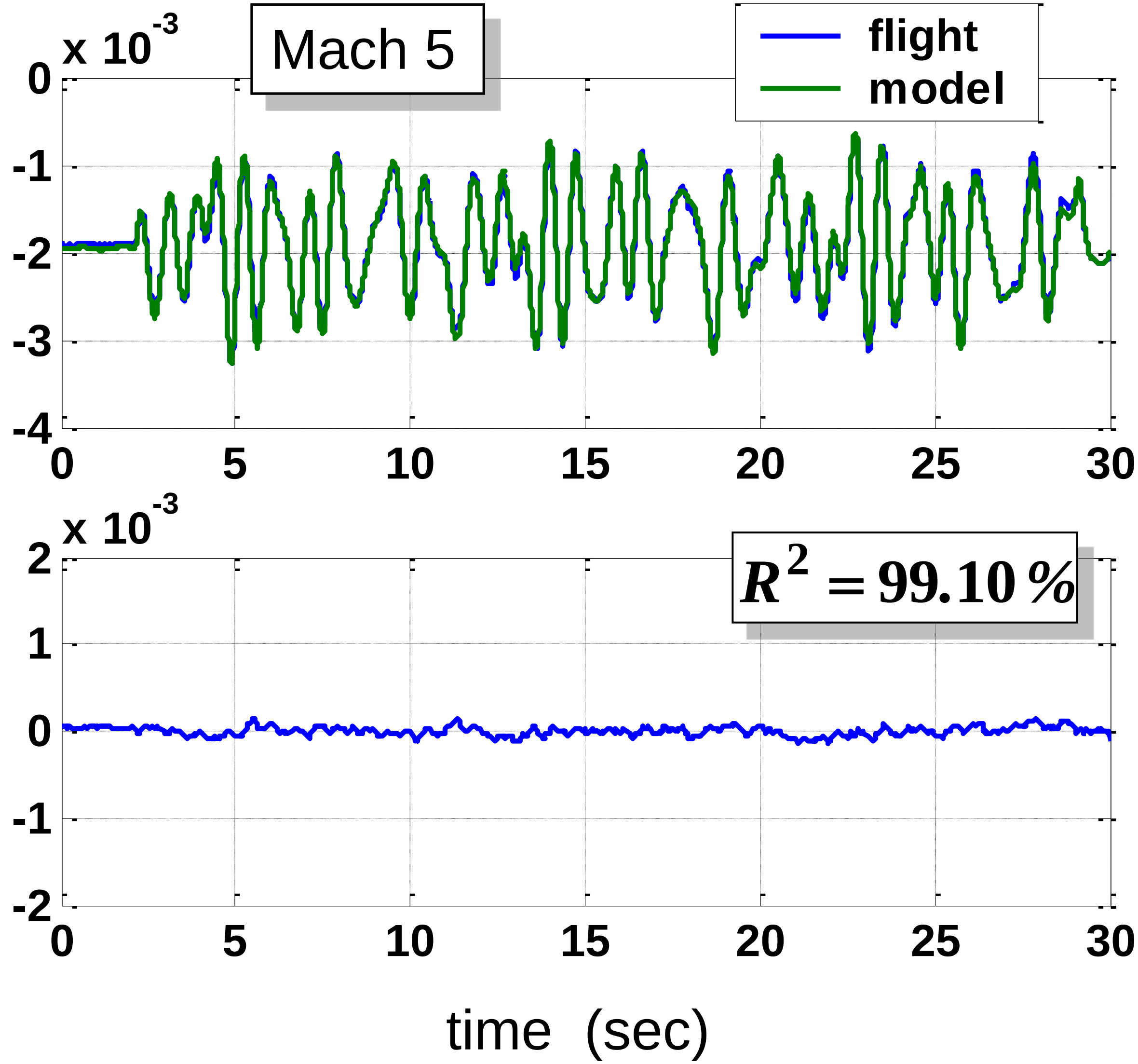
X-43A (Hyper-X)



Hyper-X Mission Profile



Model Fit to the Data



C_m

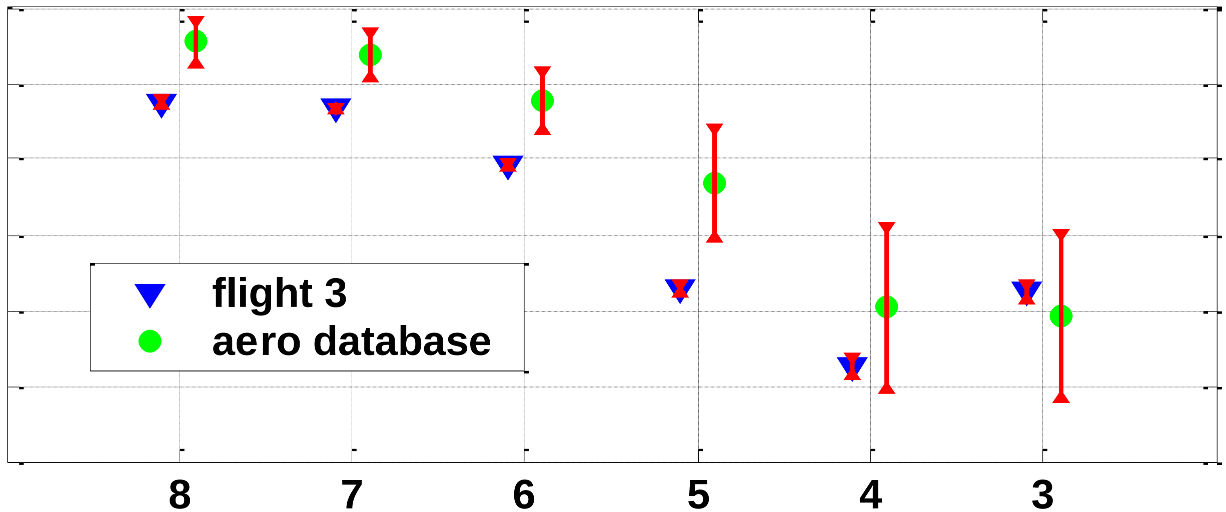
residuals

$\nu_m \equiv C_m - \hat{C}_m$

Pitching Moment Parameters

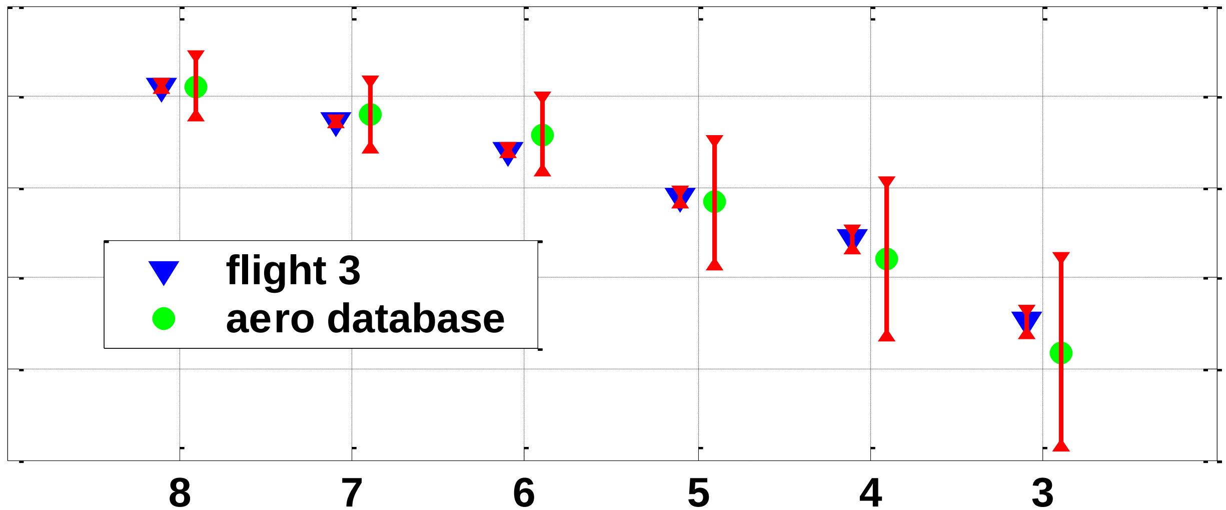
C_{m_α}

(per rad)



$C_{m_{\delta_e}}$

(per rad)



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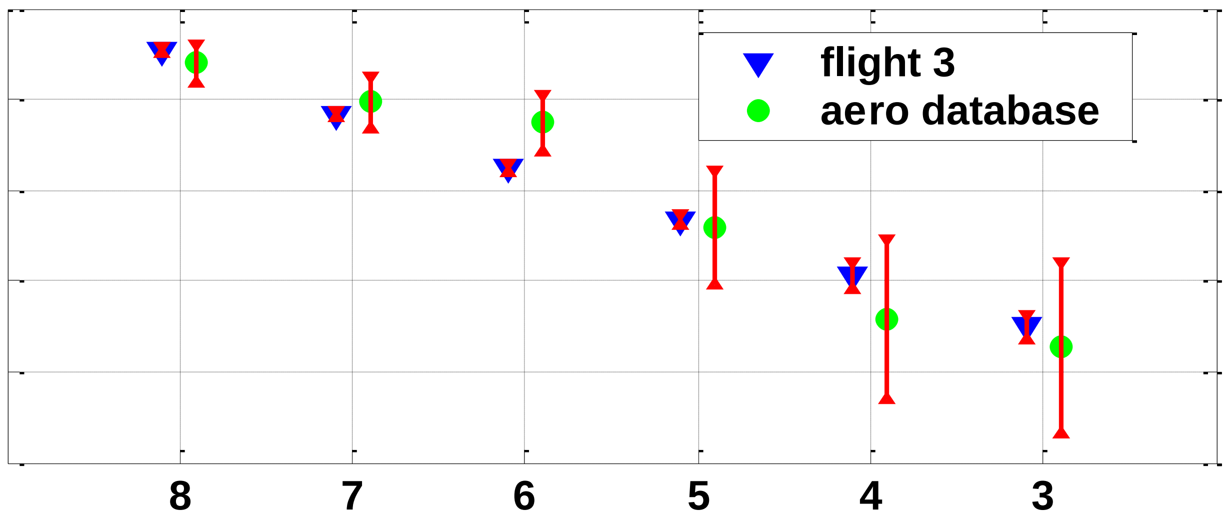
Rolling Moment Parameters

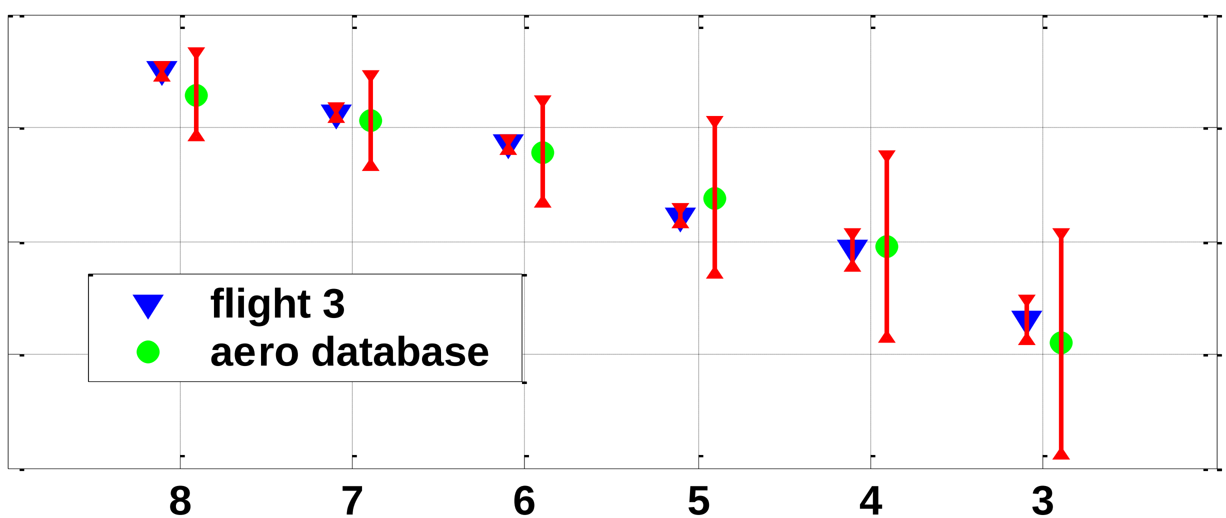
C_{l_β}

(per rad)



$C_{l_{\delta_a}}$

(per rad)



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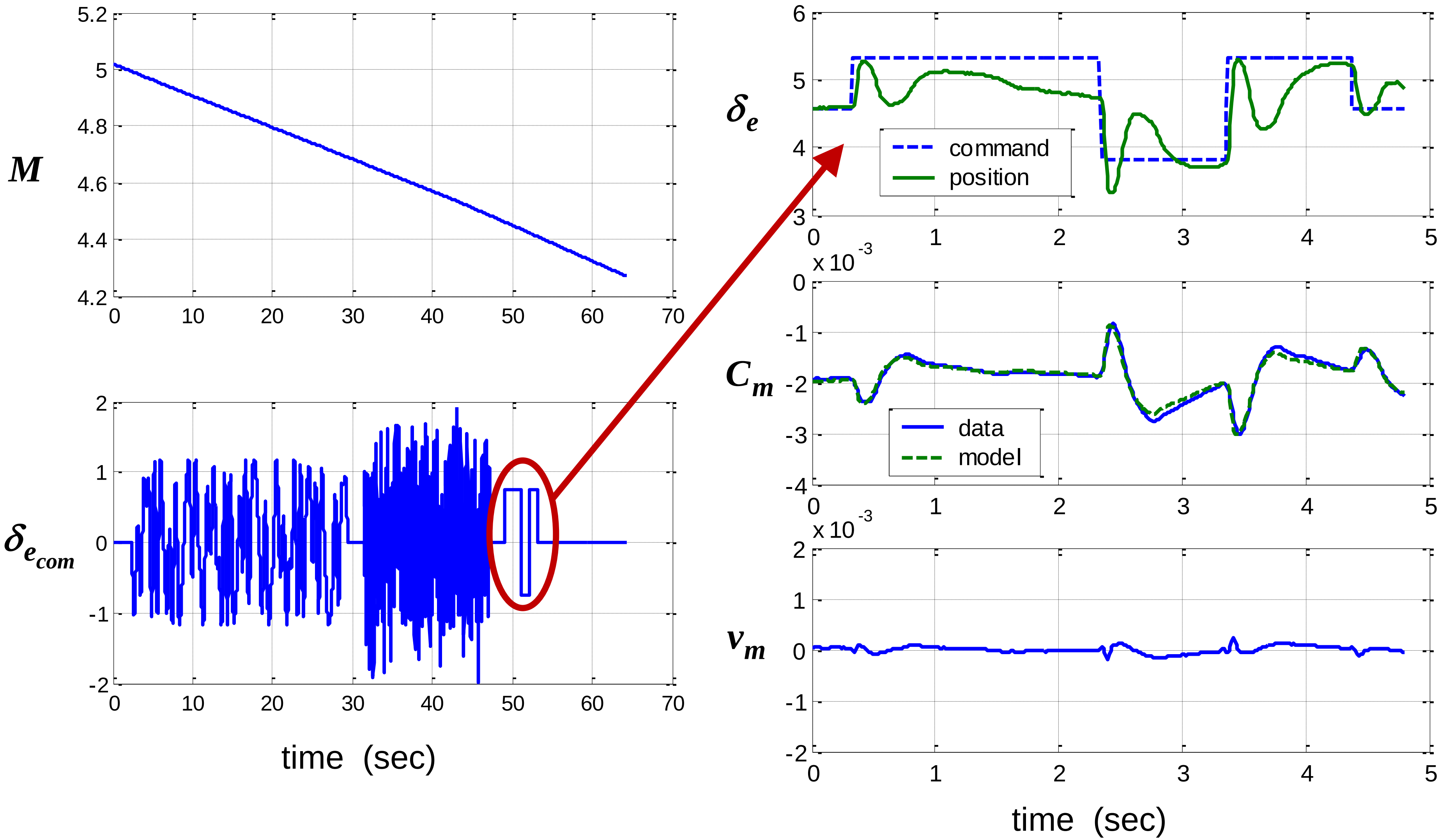
Prediction Capability



Applications

Flight Research, Envelope Expansion

Validate and Improve Predictions

Flight Simulation

Accident Investigation

Evaluate New or Modified Aircraft

Flight Control, Flying Qualities

Applications

Twin Otter

ARES I-X Launch Vehicle

X-43A (Hyper-X)

X-29A

1903 Wright Flyer Replica

Sub-scale Transport Aircraft

Tu-144LL Supersonic Transport

Global Hawk

There are many others …

Lessons Learned

- **System Identification expertise is needed right from the start of a flight test project:**
  - Instrumentation specification, sampling rate, filtering, necessary info
  - Experiment design to achieve project goals with given resources
- **Injecting optimized orthogonal multi-sine excitation signals at the actuators produces excellent data for modeling, regardless of pilot input or feedback control**
- **Iteration should be built into the flight test planning**
- **A diverse tool set is essential**
- **System Identification takes time and money – but not nearly as much as not doing it**

Questions?

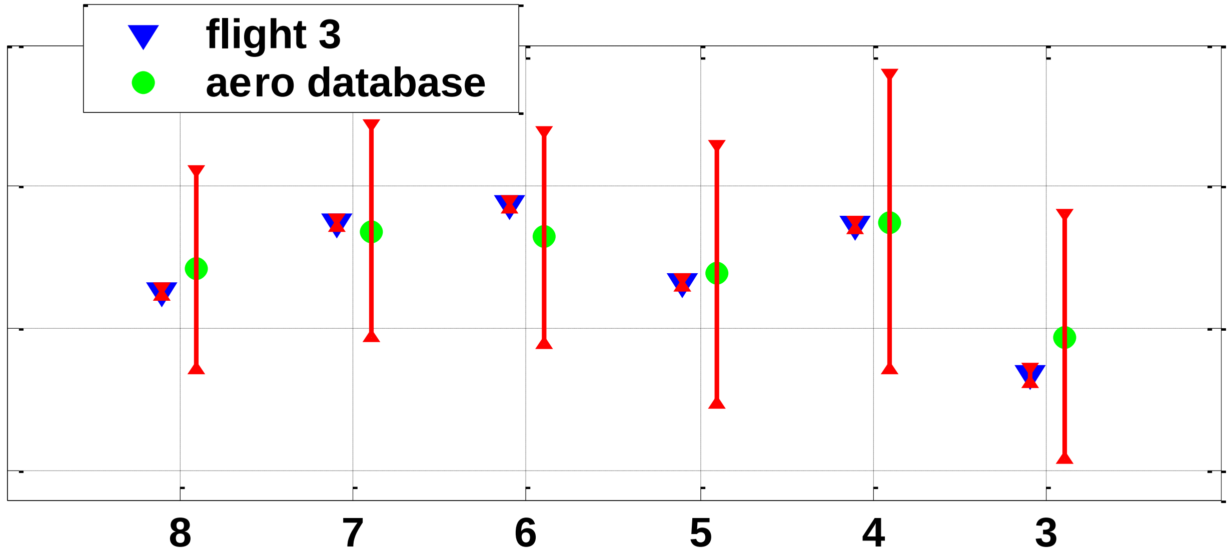
NASA

Backup

Drag Parameters

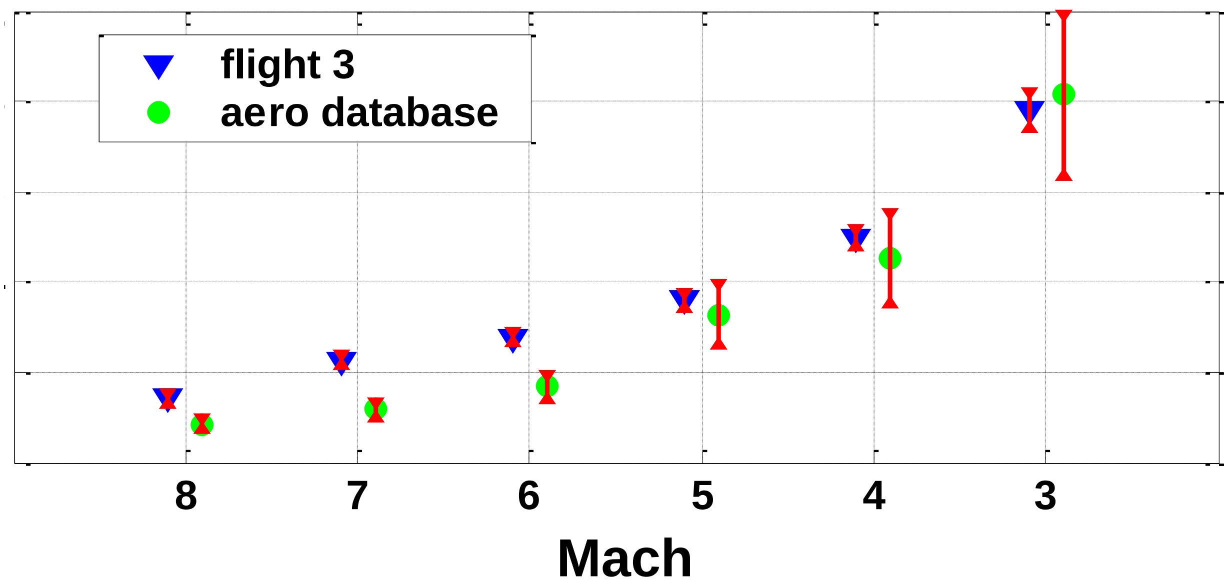
C_{D_α}

(per rad)

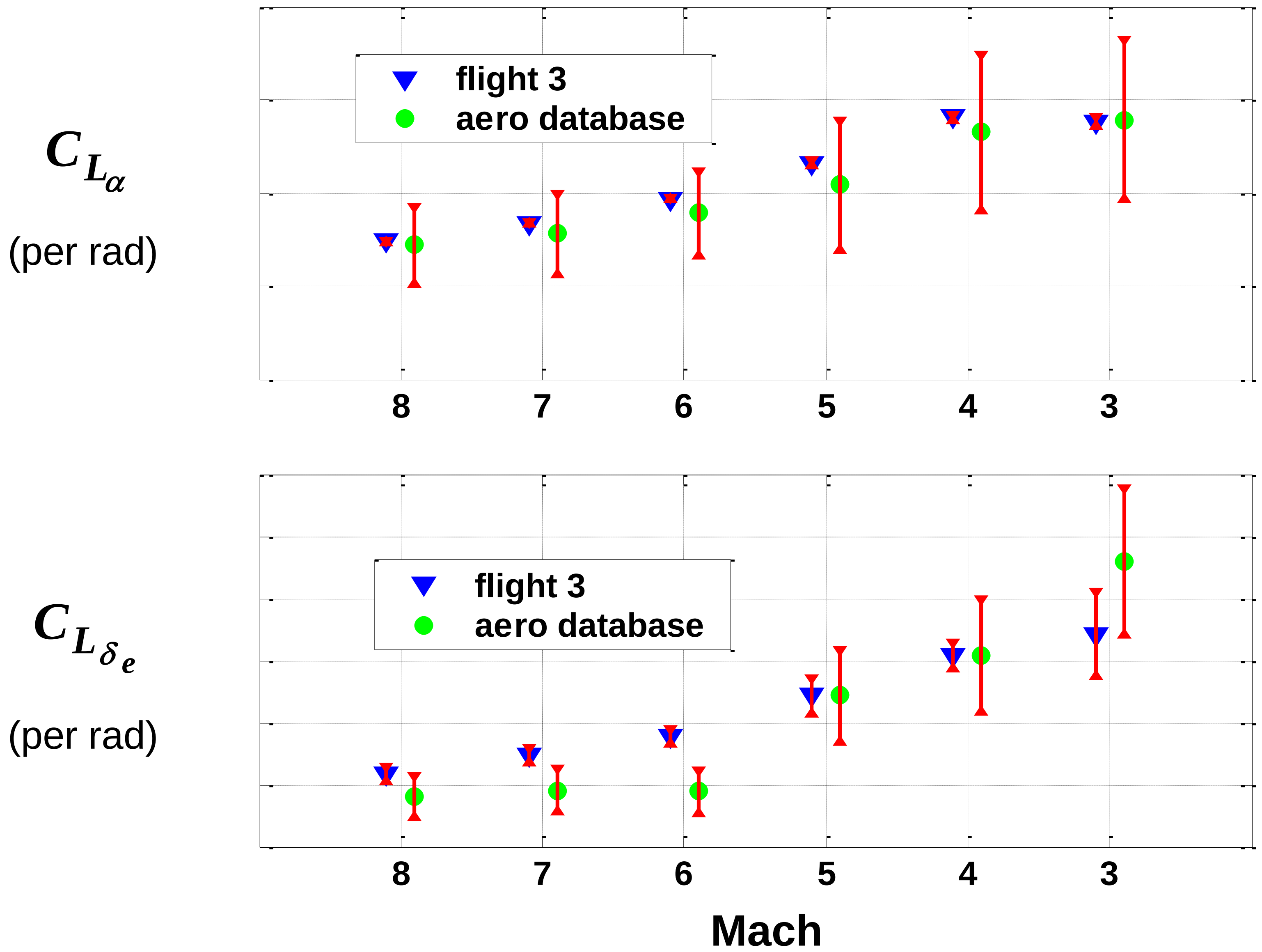


$C_{D_{\delta_e}}$

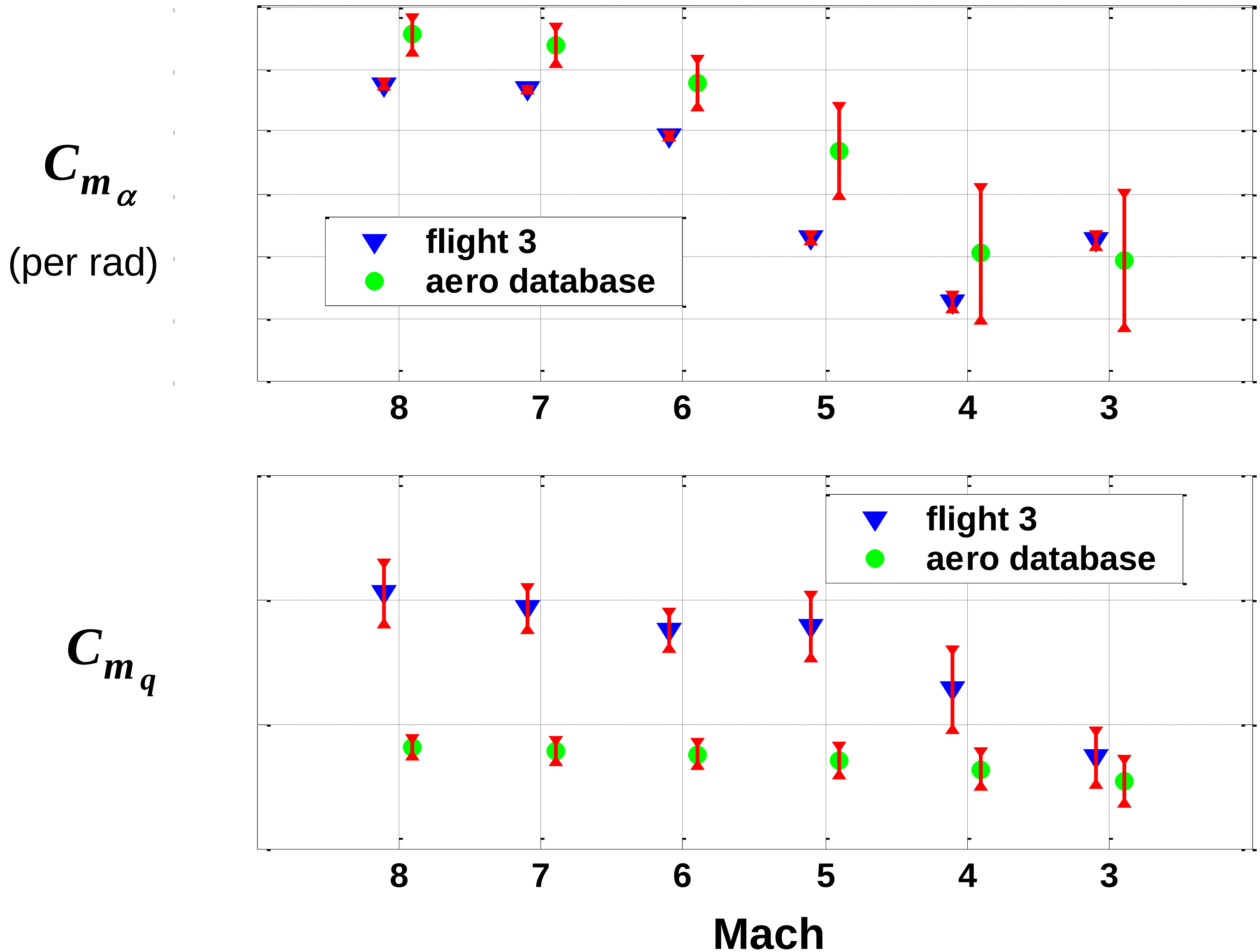
(per rad)



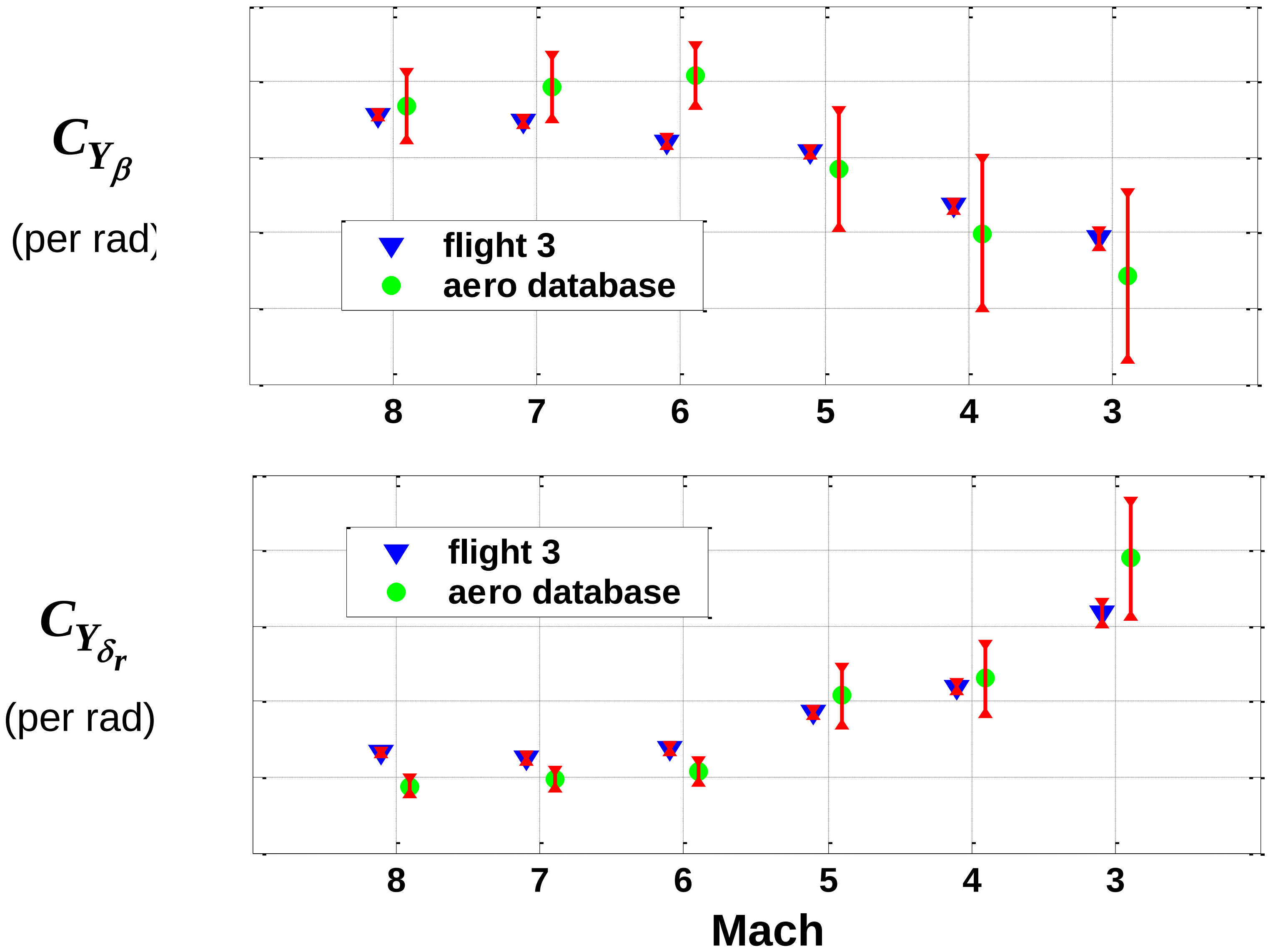
Lift Parameters



Pitching Moment Parameters



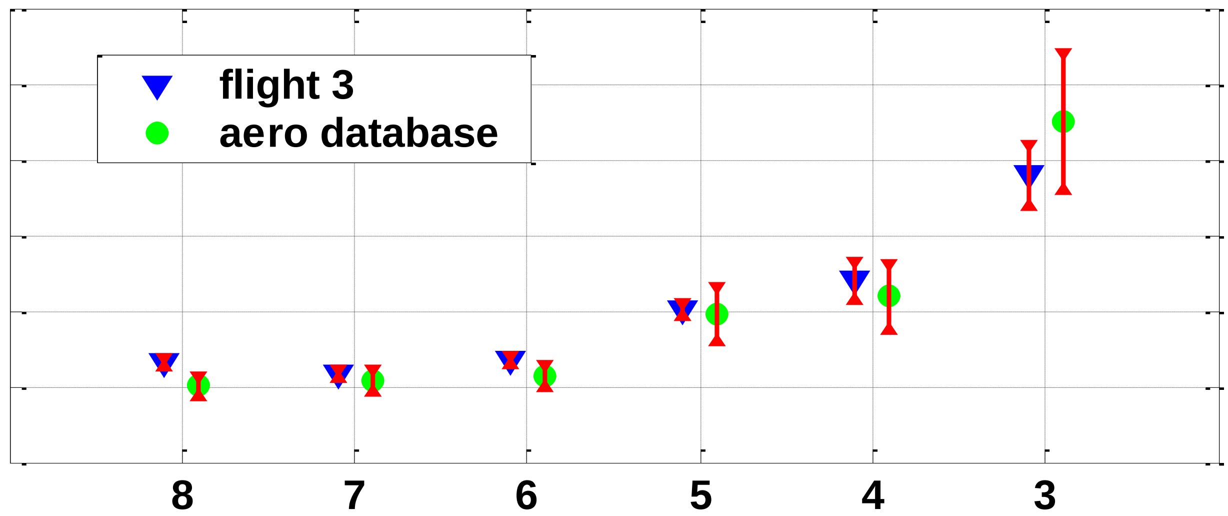
Side Force Parameters



Rolling Moment Parameters

$C_{l_{\delta_r}}$

(per rad)



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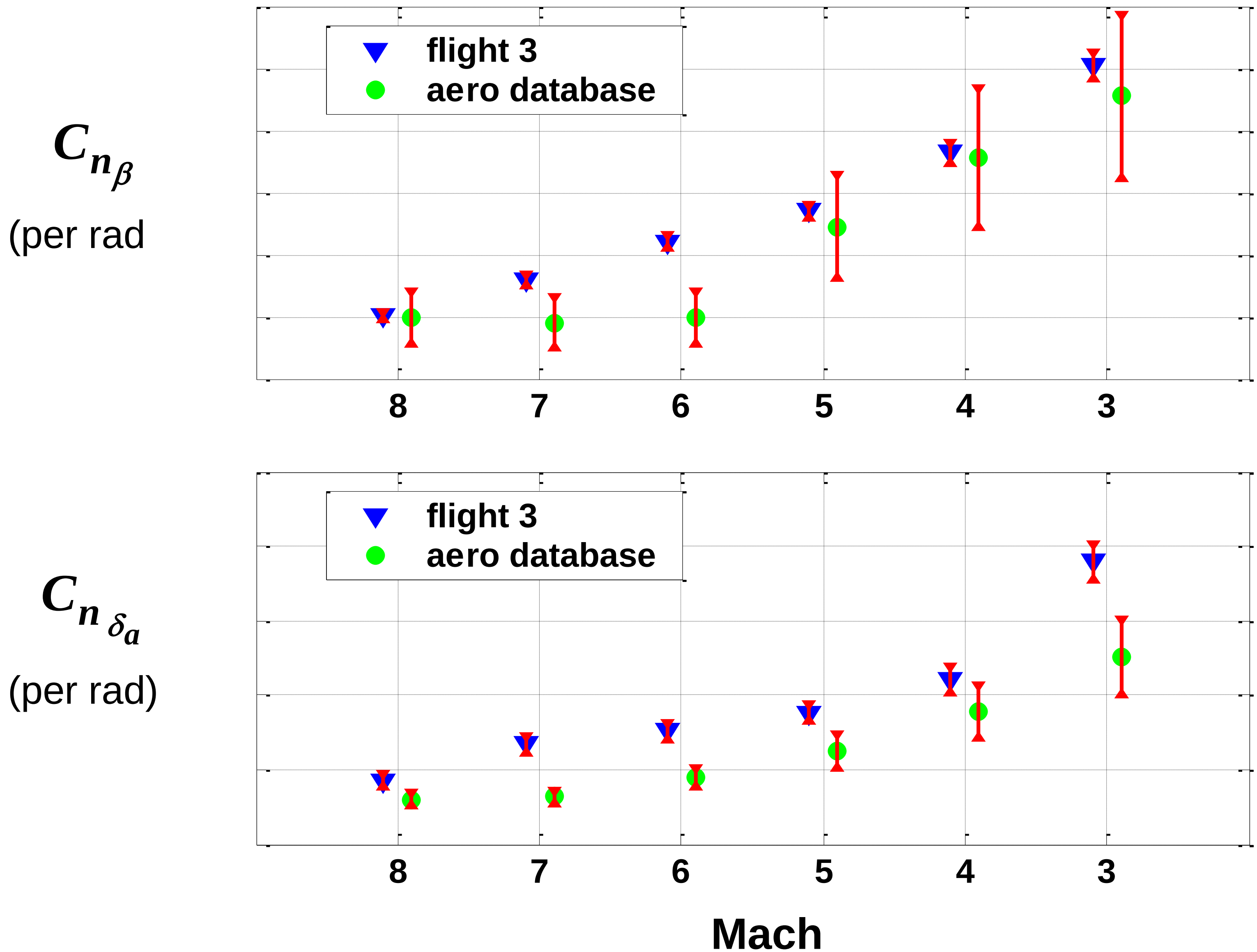
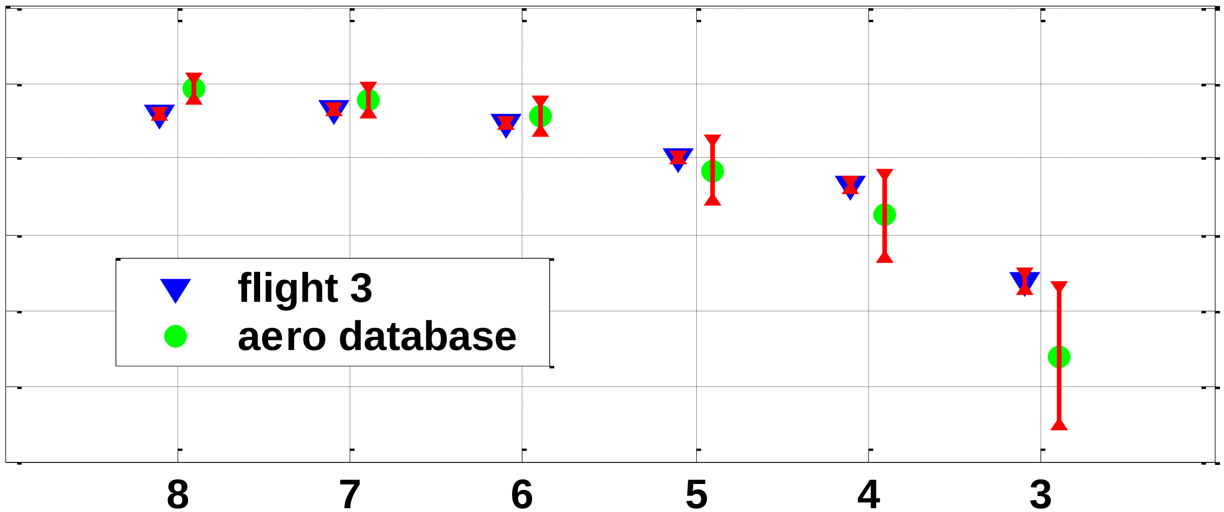
Yawing Moment Parameters



Yawing Moment Parameters

$C_{n_{\delta_r}}$

(per rad



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Input Design Features

- **Multiple input orthogonality in both time domain and frequency domain simultaneously**
- **Wide frequency range inputs for robustness to unknown vehicle dynamics**
- **Small amplitude perturbation inputs**
- **Time efficient multi-axis, multi-control excitation**
- **Produces excellent data information content**
- **Easy to design – robust and general**
- **Does not move the aircraft off nominal condition**

How Does It Work?

Pitching moment equation: $$M = I_y \dot{q} + \left(I_x - I_z\right) pr + I_{xz}\left(p^2 - r^2\right)$$

Equation-Error

$$M = I_y \dot{q} + \left(I_x - I_z\right) pr + I_{xz}\left(p^2 - r^2\right)$$

Output-Error

$$\dot{q} = \frac{1}{I_y}\left[M - \left(I_x - I_z\right) pr - I_{xz}\left(p^2 - r^2\right)\right]$$

Unknowns

Postulated model: $$\hat{M} = M_o + M_\alpha \alpha + M_q q + M_\delta \delta$$

Integrate $\longrightarrow \hat{q}$

$$J = \frac{1}{2}\left(M - \hat{M}\right)^T \left(M - \hat{M}\right)$$

$$J = \frac{1}{2}\left(q - \hat{q}\right)^T \left(q - \hat{q}\right)$$

Solve with one-shot linear algebra

Solve with iterative nonlinear optimization

What Are the Results?

Pitching moment model: $\hat{M} = M_o + M_\alpha \alpha + M_q q + M_\delta \delta$

$M_o =$ **pitching moment bias**

$M_\alpha =$ **static stability**

$M_q =$ **dynamic stability or damping**

$M_\delta =$ **pitch control authority**

Results include estimated numerical values for all unknown parameters, as well as statistical uncertainties (error bounds).

Modeling results characterize the stability and control of the aircraft

Equation-Error in the Frequency Domain

$$y = \begin{bmatrix} \xi_1 & \xi_2 & \dots & \xi_n \end{bmatrix} \theta \quad \Rightarrow \quad \tilde{y}(\omega_i) = \begin{bmatrix} \tilde{\xi}_1(\omega_i) & \tilde{\xi}_2(\omega_i) & \dots & \tilde{\xi}_n(\omega_i) \end{bmatrix} \theta$$

$\xi_i \;, \; i = 1, 2, \dots, n$	are regressors, functions of the state variables *x* and control variables *u*

Least Squares Formulation with complex numbers

$$\boxed{\tilde{z} = \tilde{X}\theta + \tilde{v}}$$

where

$$\tilde{z} = \begin{bmatrix} \tilde{z}(\omega_1) \\ \vdots \\ \tilde{z}(\omega_m) \end{bmatrix} \qquad \tilde{X} = \begin{bmatrix} \tilde{\xi}_1(\omega_1) & \tilde{\xi}_2(\omega_1) & \dots & \tilde{\xi}_n(\omega_1) \\ \vdots & \vdots & \dots & \vdots \\ \tilde{\xi}_1(\omega_m) & \tilde{\xi}_2(\omega_m) & \dots & \tilde{\xi}_n(\omega_m) \end{bmatrix}$$

Equation-Error in the Frequency Domain

Non-iterative solution:

$$\hat{\theta} = \left[Re\left(\tilde{X}^{\dagger} \tilde{X} \right) \right]^{-1} Re\left(\tilde{X}^{\dagger} \tilde{z} \right)$$

Accurate error measures:

$$Cov\left(\hat{\theta}\right) = \frac{\tilde{v}^{\dagger}\tilde{v}}{(m-n)} \left[Re\left(\tilde{X}^{\dagger} \tilde{X} \right) \right]^{-1}$$

$$\tilde{v} = \tilde{z} - \tilde{X}\hat{\theta}$$

m = no. of frequencies
n = no. of estimated parameters

Notes

- Automatic modal weighting, accurate parameter estimates
- Can be used for dimensional derivatives or non-dimensional derivatives
- Error measures do not need correction for colored residuals

It’s Not Easy

1) Aircraft are multiple-input, multiple-output, nonlinear dynamical systems with complicated, nonlinear, time-varying aerodynamics

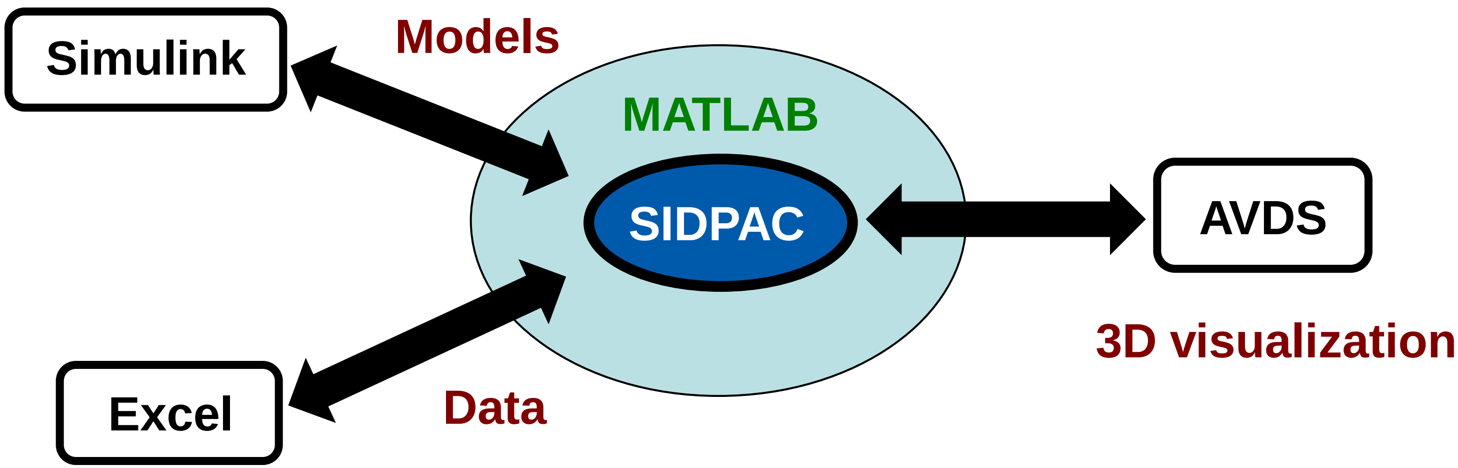
2) For an aircraft in flight, applied forces and moments must be inferred from measured responses

3) Large amounts of data must be processed

4) Aircraft measurements are noisy and sensors have practical limitations

5) Physical quantities cannot be varied independently for an aircraft in flight

System IDentification Programs for AirCraft (SIDPAC)



- SIDPAC is a collection of over 350 programs that implement a wide variety of state-of-the-art methods for aircraft system identification
- SIDPAC programs are implemented as MATLAB® M-files, and have been thoroughly tested and successfully applied to real data
- SIDPAC is used at more than 80 organization worldwide to solve aircraft system identification problems
- SIDPAC documentation is the AIAA textbook *Aircraft System Identification – Theory and Practice*, by V. Klein and E.A. Morelli

What Does SIDPAC Do?

SIDPAC tools help an analyst to:

- **Design experiments**
- **Define instrumentation requirements**
- **Filter, smooth, transform, and visualize the data**
- **Identify math models that mimic the real system**
- **Check model accuracy and predictive capability**
- **Organize, report, and use the results**

References For Further Study

P1) Iliff, K.W. (1989) "Parameter Estimation for Flight Vehicles," *Journal of Guidance, Control, and Dynamics*, Vol. 12, No. 5, pp. 609-622.

P2) Klein, V. (1989) "Estimation of Aircraft Aerodynamic Parameters from Flight Data," *Prog. Aerospace Sci.,* Vol. 26, No. 1, pp. 1-77.

P3) Hamel, P.G. and Jategaonkar, R. (1996) "Evolution of Flight Vehicle System Identification," *Journal of Aircraft*, Vol. 33, No. 1, pp. 9-28.

P4) Morelli, E.A. and Klein, V. (2005) "Application of System Identification to Aircraft at NASA Langley Research Center," *Journal of Aircraft*, Vol. 42, No. 1, pp. 12-25.

R1) Maine, R.E. and Iliff, K.W. (1986) "Application of Parameter Estimation to Aircraft Stability and Control, The Output-Error Approach," NASA RP-1168.

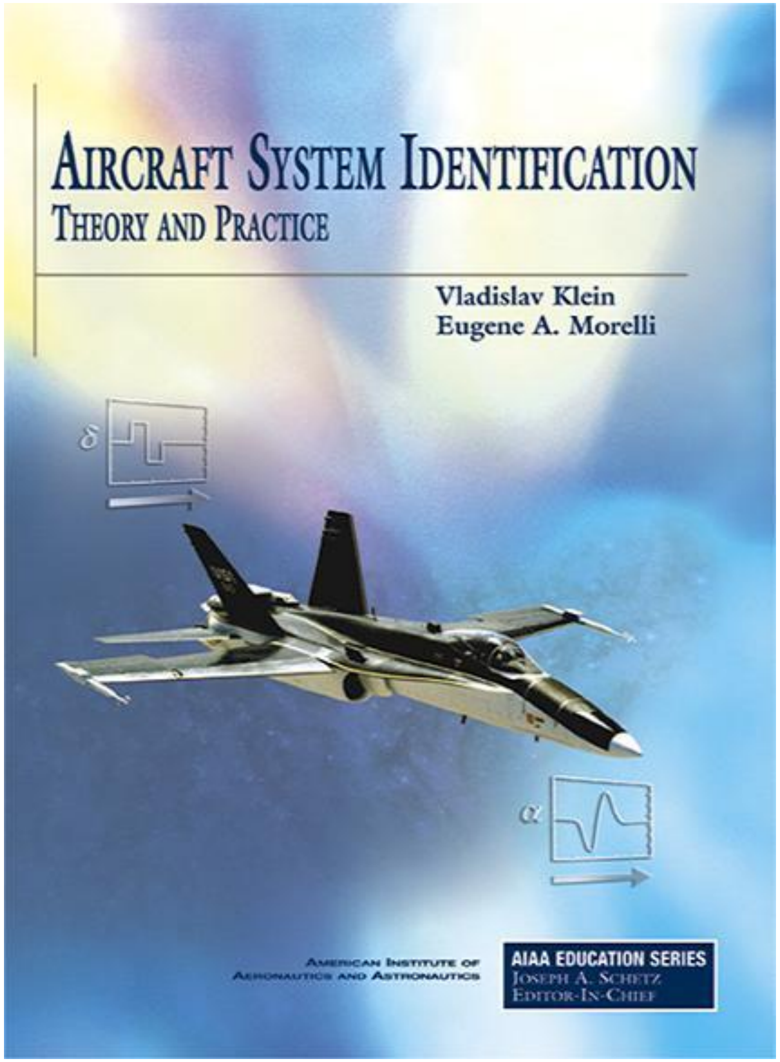
R2) Maine, R.E. and Iliff, K.W. (1985) "Identification of Dynamic Systems, Theory and Formulation," NASA RP-1138.

B1) Klein, V. and Morelli, E.A. (2006) *Aircraft System Identification - Theory and Practice*, AIAA Education Series, Reston, VA.

B2) Tischler, M.B. and Remple, R.K. (2006) *Aircraft and Rotorcraft System Identification*, AIAA Education Series, Reston, VA.

B3) Jategaonkar, R.V. (2006) *Flight Vehicle System Identification: A Time Domain Methodology*, AIAA, Reston, VA.

Textbook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Feedback and Questions

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