Determining Aircraft Moments of Inertia from Flight Test Data

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AIAA SciTech Forum

January 20, 2021

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- Flight Test Maneuver
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- E1 Flight Test Results
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Introduction

Uses for Aircraft Moments of Inertia:

- Nondimensional aerodynamic modeling
- Simulation and dynamic analysis

Conventional Methods Used:

- Ground testing
- Computer-Aided Design (CAD)
- ***Costly and time-consuming***

Can aircraft moments of inertia be determined accurately from flight test data?

Modeling Approach

Nonlinear Rotational Equations of Motion

≈ 0 for idle power

Pitch:

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

≈ 0 for idle power

Yaw:

$$\dot{r} = N + \frac{\left(I_x - I_y\right)}{I_z} pq + \frac{I_{xz}}{I_z}\left(\dot{p} - qr\right) - \cancel{\frac{I_p}{I_z}} \Omega_p q$$

Equation-Error Modeling

$$\dot{q} = \boxed{M_o \bar{q} + M_\alpha \bar{q} \alpha + M_q \bar{q} \frac{q}{V} + M_{\delta_e} \bar{q} \delta_e} + c_3 pr + c_4 \left(r^2 - p^2 \right)$$

$$\dot{r} = \boxed{N_o \bar{q} + N_\beta \bar{q} \beta + N_p \bar{q} \frac{p}{V} + N_r \bar{q} \frac{r}{V} + N_{\delta_a} \bar{q} \delta_a + N_{\delta_r} \bar{q} \delta_r} + c_5 \, pq + c_6 \left(\dot{p} - qr \right)$$

$$c_3 = \left(I_z - I_x \right) / I_y \qquad c_4 = I_{xz} / I_y$$

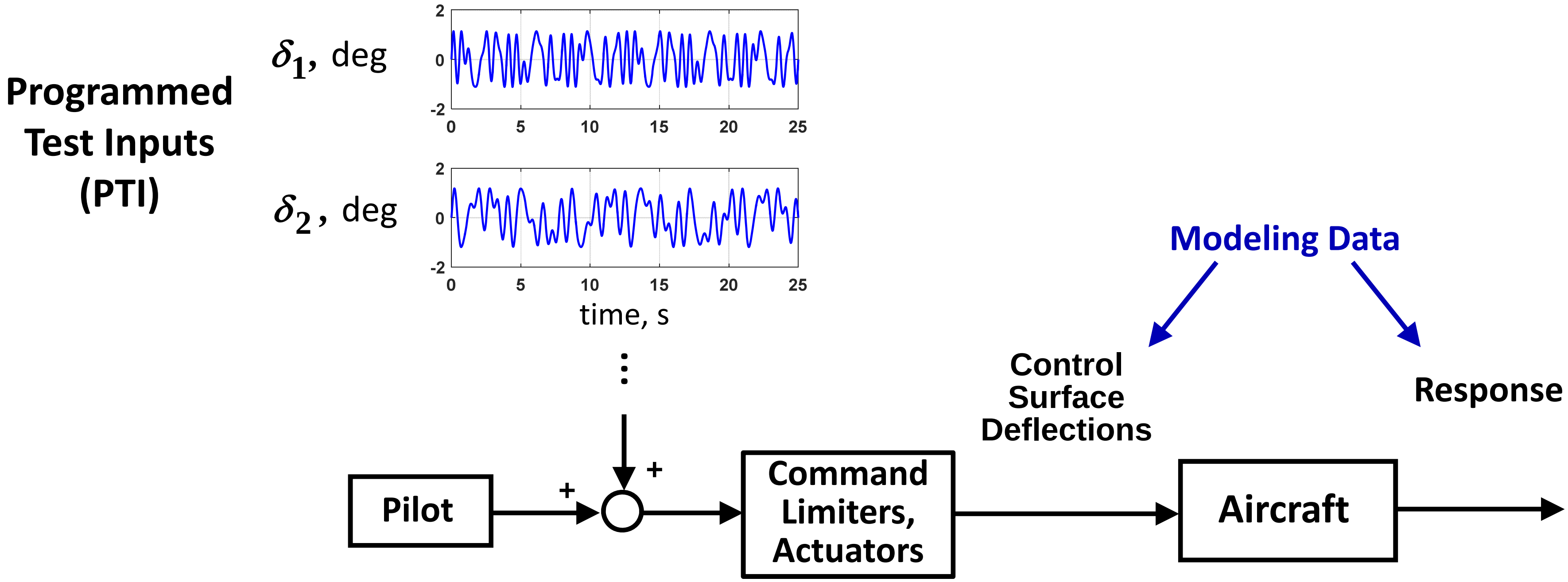
$$c_5 = \left(I_x - I_y \right) / I_z \qquad c_6 = I_{xz} / I_z$$

Flight Test Maneuver

- High angular rates to make the nonlinear inertia terms significant
- Idle power to make propulsion gyroscopic terms negligible
- Low nominal angle of attack for linear aerodynamics
- Control surface excitations for decorrelated explanatory variables

Rolls into descending turns at idle power and low nominal angle of attack with automated multi-axis orthogonal perturbation inputs on the control surfaces

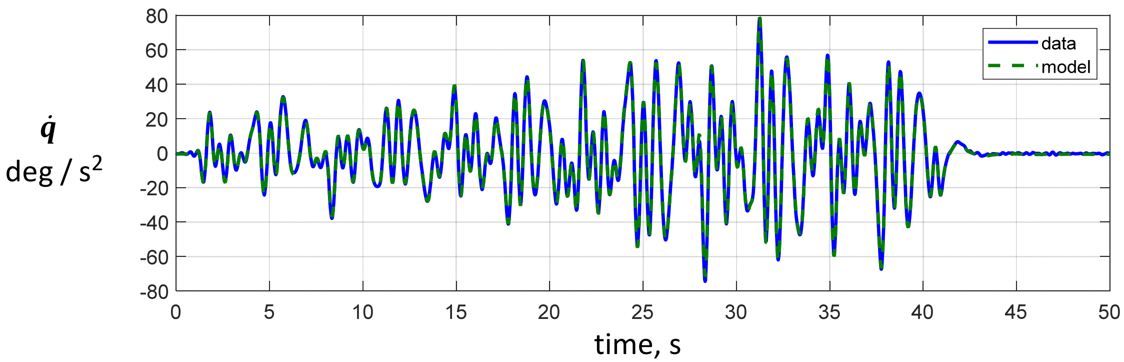
Flight Test Maneuver

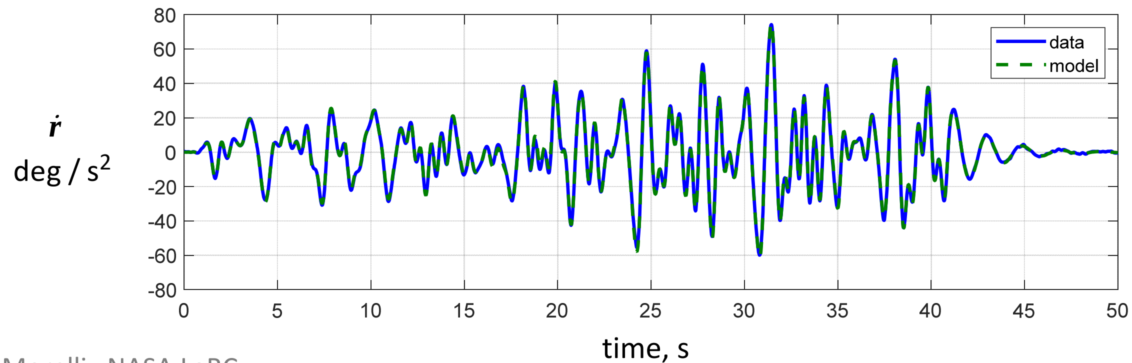


F-16 Nonlinear Simulation: Desktop joystick
E1 Flight Test: Radio Control from the Ground

F-16 Nonlinear Simulation Results

Single maneuver, alternating rolls into descending turns with PTI active





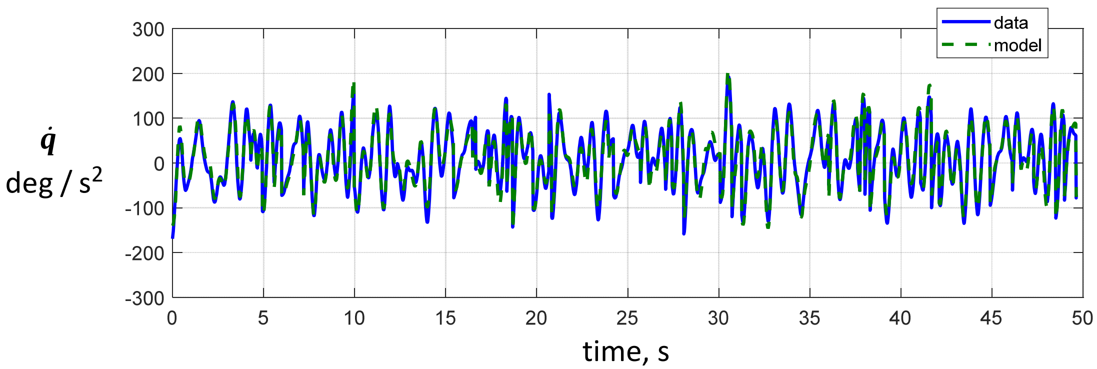
F-16 Nonlinear Simulation Results

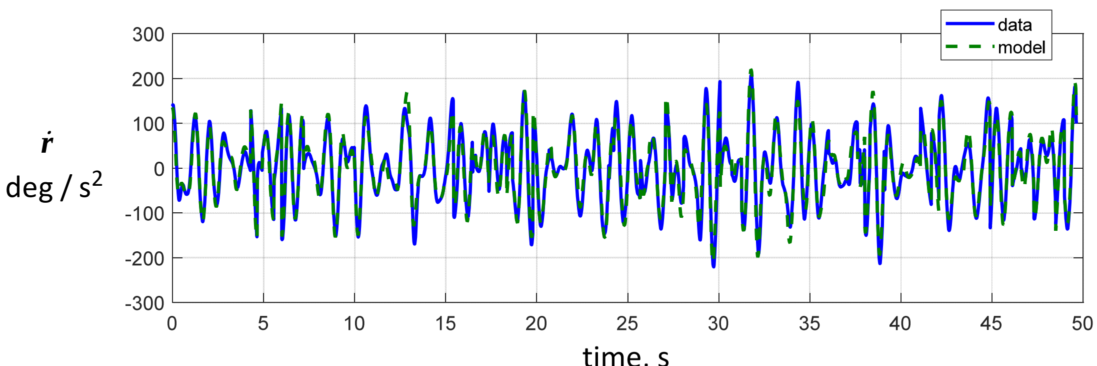
Linear Estimation

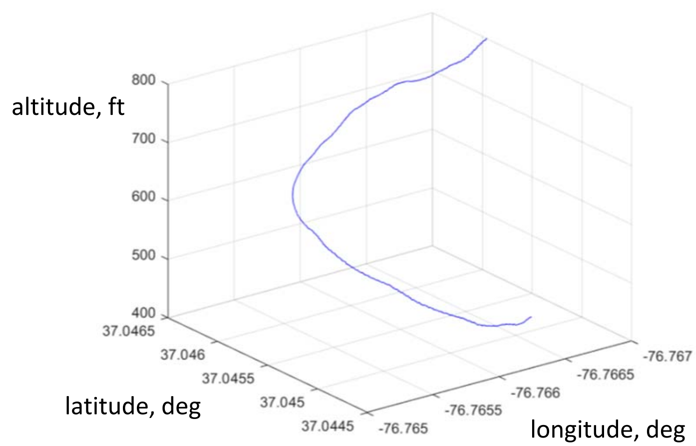
Parameter	True	Estimate ± Standard Error	Percent Error
c_3	0.9604	0.9643 ± 0.0234	0.40
c_4	0.0176	0.0166 ± 0.0019	–5.68
c_5	–0.7340	–0.7517 ± 0.0189	–2.41
c_6	0.0156	0.0147 ± 0.0011	–5.25

E1 Flight Test Results

Five maneuvers, descending turns with PTI active, $\alpha \leq$ 7 deg







E1 Flight Test Results

Nonlinear Estimation

Parameter	Ground Test Estimate*	Flight Test Estimate ± Standard Error	Percent Error
I_x	2.964	3.053 ± 1.002	3.01
I_y	8.776	8.711 ± 0.732	–0.74
I_z	11.716	11.036 ± 0.495	–5.80
I_{xz}	0.750	0.779 ± 0.107	3.89

* Ground test uncertainty ≤ 3 %

Summary:

A novel flight test method for accurately determining moments of inertia was developed and demonstrated

Key Findings:

- Large-amplitude piloted flight test maneuvers at idle power with multi-axis orthogonal excitations produced informative flight data for accurately determining aircraft moments of inertia
- Simple and versatile equation-error model formulation produced accurate results for both F-16 nonlinear simulation and E1 flight test
- Costly and time-consuming ground testing or CAD modeling can be avoided

Questions?

Backup Slides

Equation-Error Solution

- Data can be selected from multiple maneuvers and need not be contiguous in time
- Linear estimation for inertia constants $c_3,\ c_4,\ c_5,\ c_6$
- Nonlinear parameter estimation for inertia tensor elements $I_x,\ I_y,\ I_z,\ I_{xz}$
- Modeling function data are smoothed for modeling accuracy
- Straightforward solutions using SIDPAC

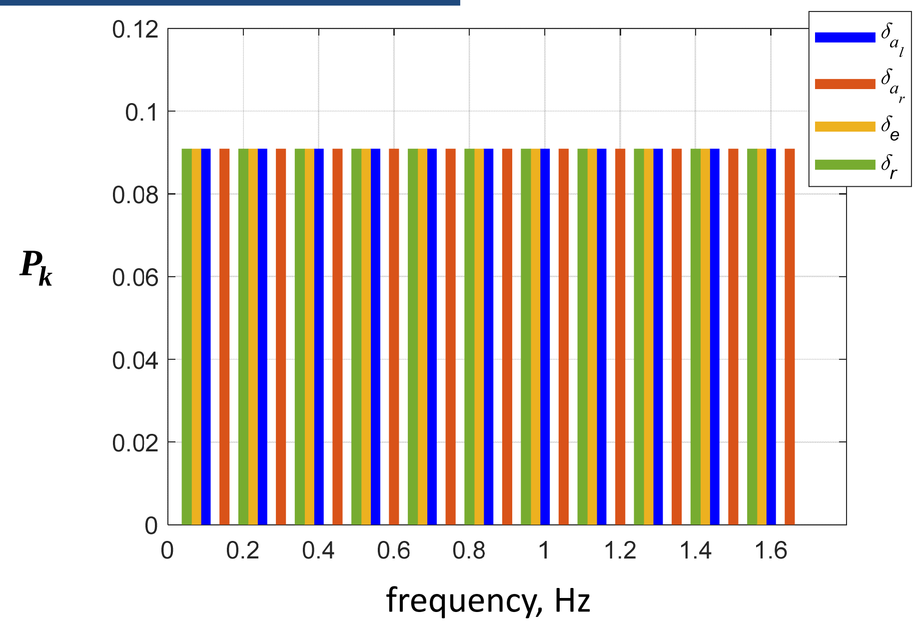
Orthogonal Optimized Multisine Inputs

Programmed Test Input (PTI) Design

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

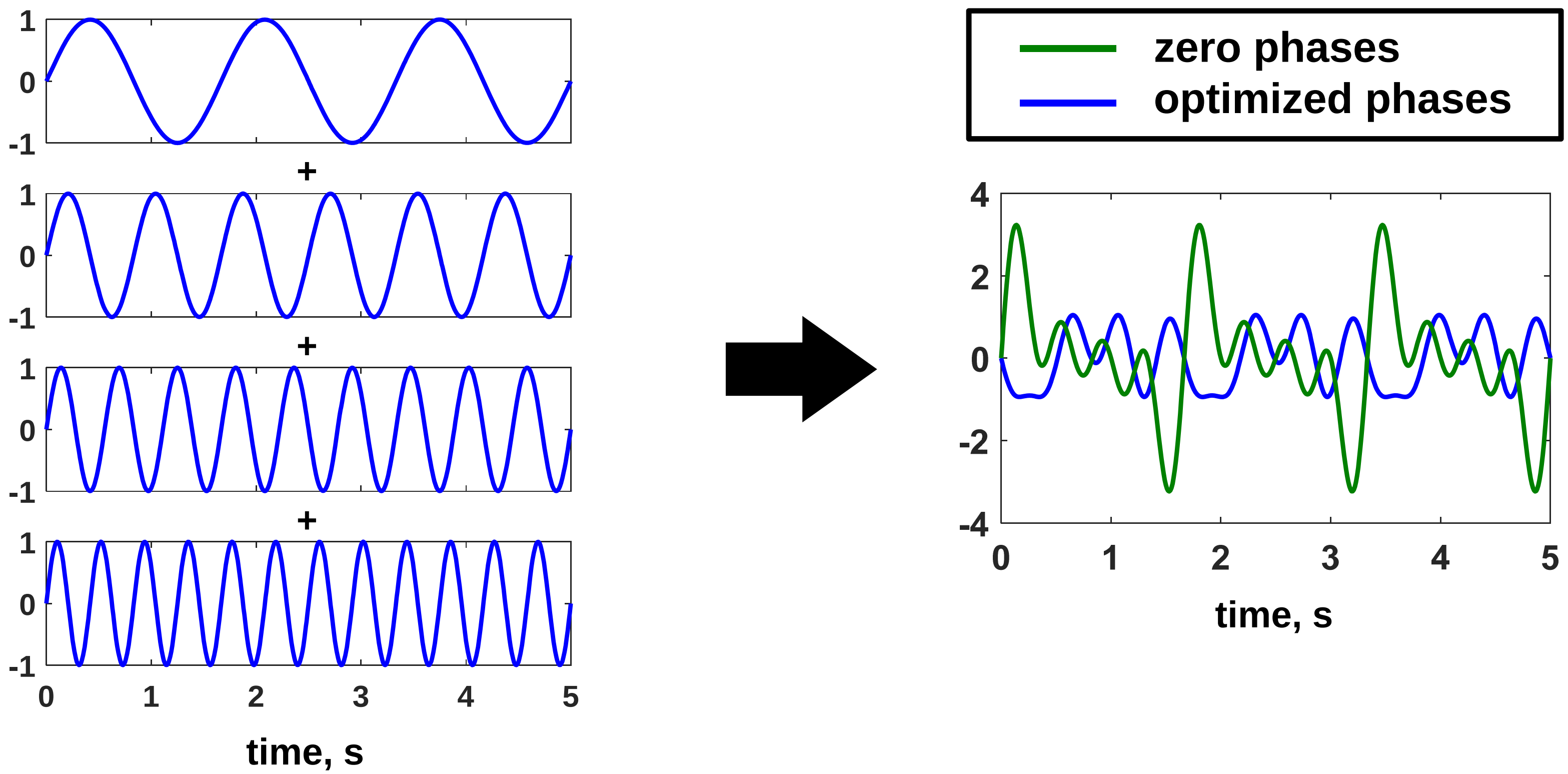
$T =$ maneuver length, s

- Time/Frequency orthogonal
- Simultaneous multi-input
- Robust to various dynamics
- Balanced, minimal excursions
- Easy to design
- Successful in past flight tests



Phases ϕ_k optimized for minimum peak-to-peak amplitude of the sum

Multisine Phase Optimization



Orthogonal Optimized Multisine Inputs

- Inputs are mutually orthogonal in the time and frequency domains
  - Flexibility to model in time or frequency domain
  - Simultaneous input excitation for high efficiency
  - Decorrelates explanatory variables and provides good coverage
- Phases optimized for minimum perturbation amplitudes and the inputs are balanced – maneuver does not move aircraft off nominal trajectory
- Wide-band frequency content for robustness and varied flight conditions
- Easy to design, successful on many other flight tests