Recent System Identification Research at NASA Langley Research Center

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Special Issue in the AIAA Journal of Aircraft

https://arc.aiaa.org/journal/ja

Title: "Advances in Aircraft System Identification from Flight Test Data"

Editors: Jared A. Grauer and Eugene A. Morelli

10 papers from centers around the world in government, industry, and academia sectors

Publication expected mid 2023

Outline

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Aircraft System Identification Overview

Experiment Design

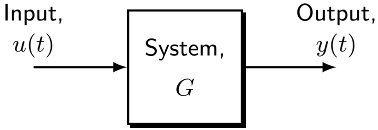
Frequency Response Identification

Modeling in Turbulence

Aeroelastic Modeling

Conclusions

Problems in Dynamic Systems

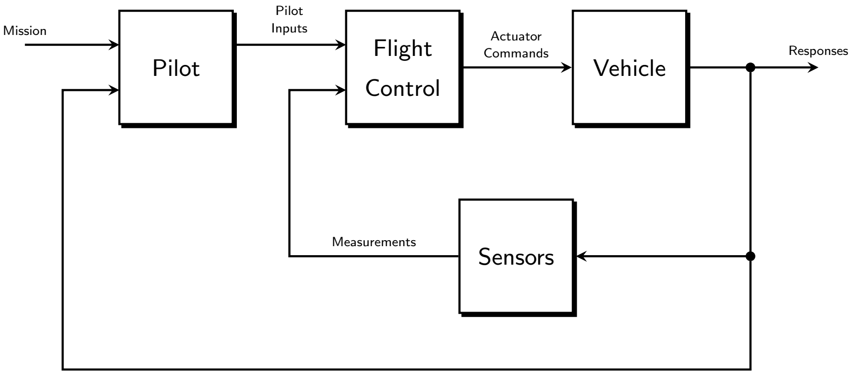


Simulation: Given $u(t)$ and G, predict $y(t)$

Control: Given G and a desired $y(t)$, design $u(t)$

Identification: Given $u(t)$ and $y(t)$, estimate G

Aircraft Systems of Interest



Primary Uses of Aircraft System Identification

- Validate analytical models or wind tunnel data
- Verify control law implementation
- Updating simulations and control laws
- Checking robustness

Wide Range of Modeling Techniques at LaRC

Matching different responses

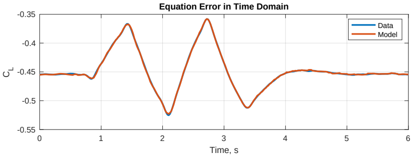
- Measured time histories
- Fourier transforms
- Frequency responses

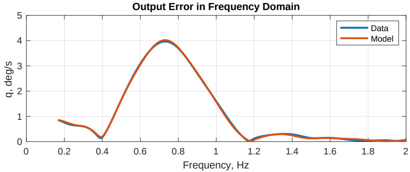
Maximum likelihood estimation

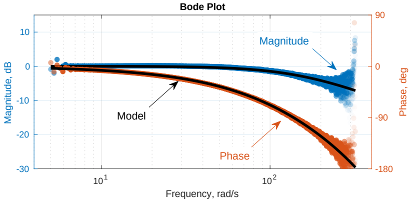
- Theoretical underpinning
- Accurate uncertainty analysis
- Equation error and output error

Characteristics

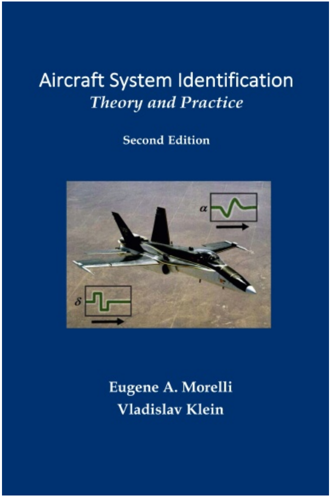
- Efficient flight test
- Real-time identification
- Multiple input, multiple output
- Closed-loop testing

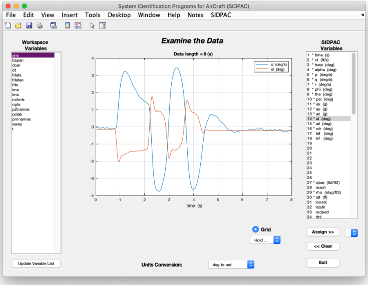






Textbook and SIDPAC Software





SIDPAC = System IDentification Programs for AirCraft

`https://software.nasa.gov`

Selected Aircraft Examples

T-2

Credit: NASA LaRC

X-56A

Credit: NASA AFRC

Modified F-15B

Credit: NASA AFRC

Ares I-X

Credit: NASA LaRC

X-43A Hyper-X

Credit: NASA LaRC

Bat-4

Credit: NASA LaRC

E1

Credit: NASA LaRC

S-2

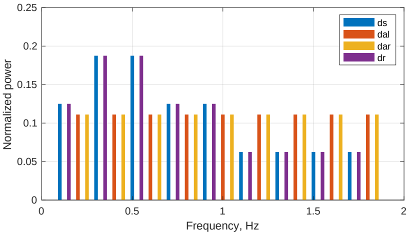
Credit: NASA LaRC

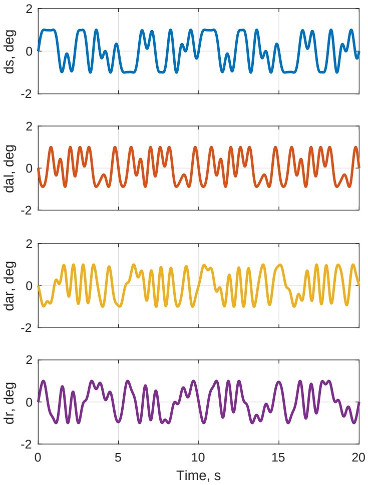
Morelli and Grauer, "Advances in Aircraft System Identification at NASA Langley Research Center," expected 2023

Outline

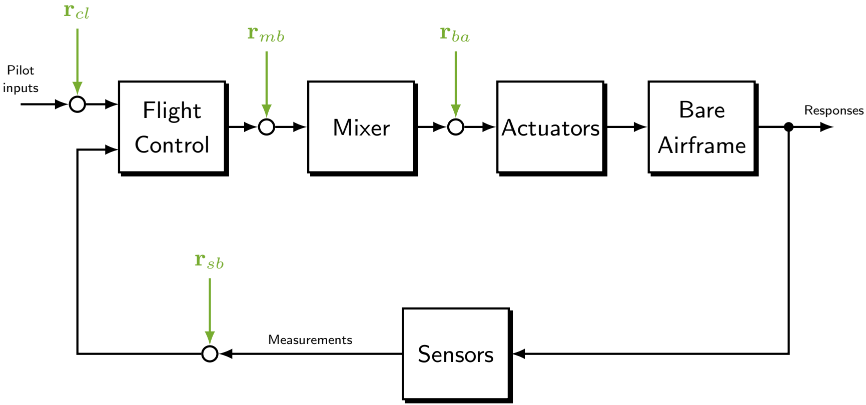
Orthogonal Phase-Optimized Multisine Inputs

$$r_j(t) = \sum_{k \in K_j} a_k \sin\left(\frac{2\pi k}{T} t + \phi_k\right)$$





Locations for Injecting Excitations



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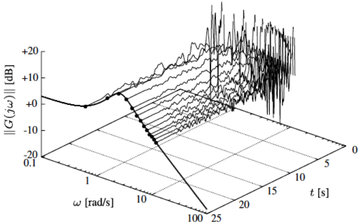
Open-Loop Frequency Responses in Real Time

$$u(j\omega_k) = \Delta t \sum_{i=1}^{N} u(t_i)\, e^{-j\omega_k t_i}$$

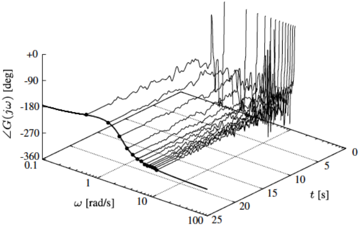
$$y(j\omega_k) = \Delta t \sum_{i=1}^{N} y(t_i)\, e^{-j\omega_k t_i}$$

$$\hat{G}(j\omega_k) = \frac{y(j\omega_k)}{u(j\omega_k)}$$

Credit: NASA Langley Research Center



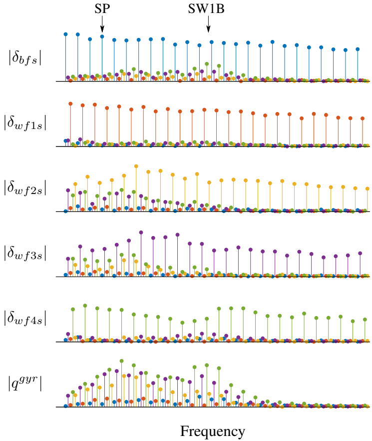
a) Magnitude evolution

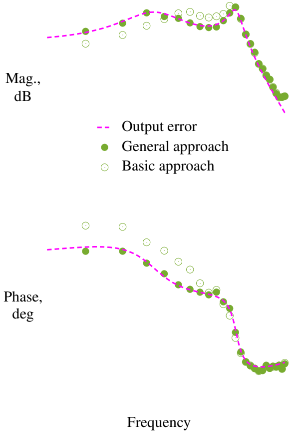


b) Phase angle evolution

Grauer and Morelli, “Method for Real-Time Frequency Response and Uncertainty Estimation,” 2014

Open-Loop Estimation from Closed-Loop Data





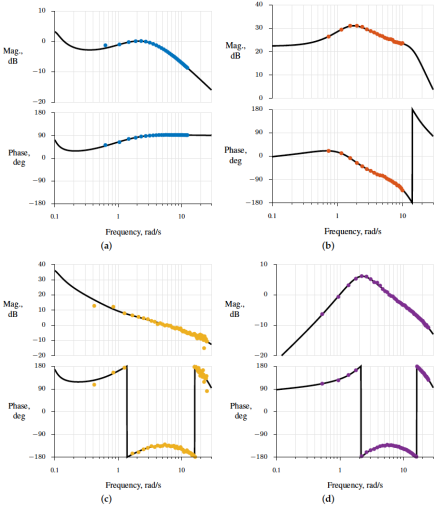
Grauer and Boucher, "Real-Time Estimation of Bare-Airframe Frequency Responses from Closed-Loop Data and Multisine Inputs," 2020

Multiple-Loop Frequency Response Estimation

- Bare airframe
- Closed-loop system
- Open loop at mixer
- Open loop at sensor

Credit: NASA / Lockheed Martin

Credit: NASA / Jim Ross



Grauer, "Frequency Response Estimation for Multiple Aircraft Control Loops using Orthogonal Phase-Optimized Multisine Inputs," 2022

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- Aircraft System Identification Overview
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- **Modeling in Turbulence**
- Aeroelastic Modeling
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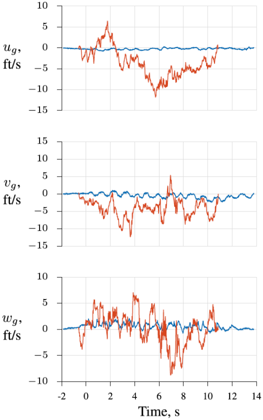
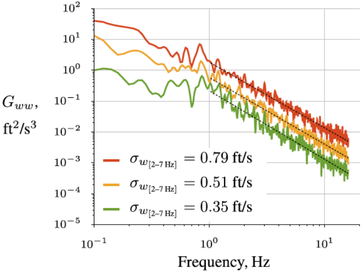
Reconstructed Turbulence as a Measured Input

Basic concept: $\alpha_m = \alpha + \alpha_g - \dfrac{lq}{V}$

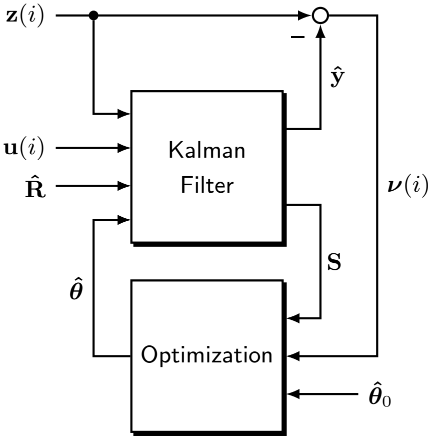


Credit: NASA Langley Research Center



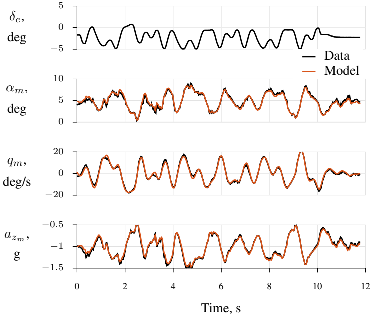
Grauer, "Aerodynamic Parameter Estimation Using Reconstructed Turbulence Measurements," 2021

Parameter Estimation Considering Process Noise



Grauer and Morelli, "A New Formulation of the Filter-Error Method for Aerodynamic Parameter Estimation in Turbulence," 2015

Credit: NASA Langley Research Center

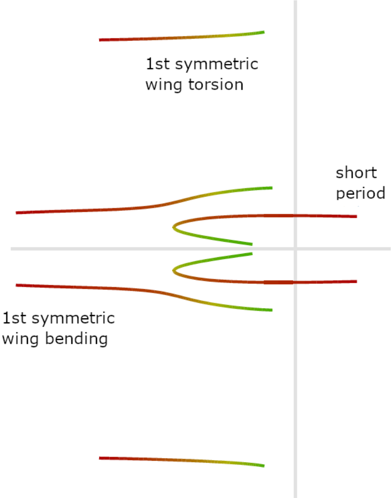


Outline

X-56A Aeroelastic Model Identification

Credit: NASA / Jim Ross

$$\begin{bmatrix} \dot{\mathbf{x}}_r \\ \dot{\mathbf{x}}_e \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{rr} & \mathbf{A}_{re} \\ \mathbf{A}_{er} & \mathbf{A}_{ee} \end{bmatrix} \begin{bmatrix} \mathbf{x}_r \\ \mathbf{x}_e \end{bmatrix} + \begin{bmatrix} \mathbf{B}_r \\ \mathbf{B}_e \end{bmatrix} \mathbf{u}$$



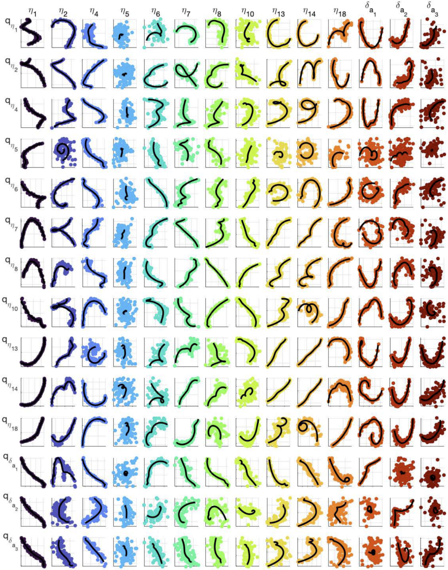
Grauer, "Identification of Aeroelastic Models for the X-56A Longitudinal Dynamics

Using Multisine Inputs and Output Error in the Frequency Domain," 2019

Unsteady Aerodynamics ROM from CFD

Credit: NASA Langley Research Center / Patrick Heaney

Computed the full 14×14 frequency response matrix from a single CFD run.



Grauer, Waite, and Stanford, "Reduced-Order Aerodynamic Modeling Based on CFD Frequency Responses from Multisine Inputs," 2021

Outline

Conclusions

Many uses for aircraft system identification

Helpful to have a wide range of modeling tools

Expect continued importance of

- Real-time identification
- Rapid model updating
- Aeroelastic systems
- Distributed sensing
- Non-conventional vehicle configurations

Selected References

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- Grauer, J.A., and Morelli, E.A., "A New Formulation of the Filter-Error Method for Aerodynamic Parameter Estimation in Turbulence," AIAA Atmospheric Flight Mechanics Conference, 2015, doi: 10.2514/6.2015-2704.
- Grauer, J.A., and Boucher, M.J., "Identification of Aeroelastic Models for the X-56A Longitudinal Dynamics Using Multisine Inputs and Output Error in the Frequency Domain," *Aerospace*, 2019, doi: 10.3390/aerospace6020024.
- Grauer, J.A., and Boucher, M.J., "Real-Time Estimation of Bare-Airframe Frequency Responses from Closed-Loop Data and Multisine Inputs," *Journal of Guidance, Control, and Dynamics*, 2020, doi: 10.2514/1.G004574.
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- Morelli, E.A., and Grauer, J.A., "Advances in Aircraft System Identification at NASA Langley Research Center," *Journal of Aircraft*, expected 2023.