



System Identification of the X-56A from Flight Test Data — Status Update

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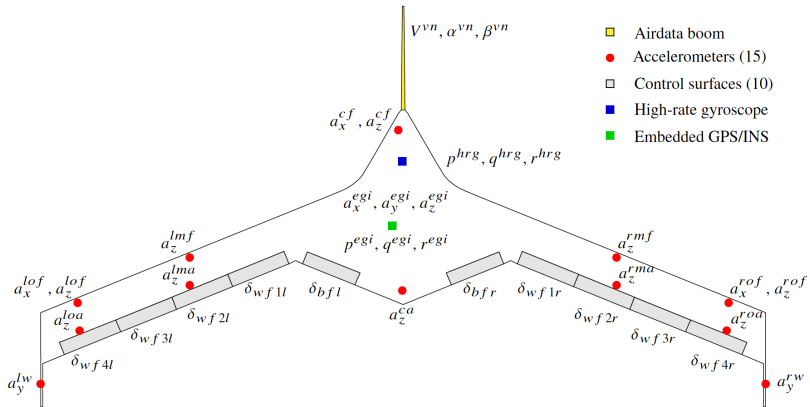
Third Aeroelastic Prediction Workshop (AePW-3)
AIAA SciTech Forum
21–22 January 2023
National Harbor, MD

X-56A MUTT Aeroelastic Demonstrator

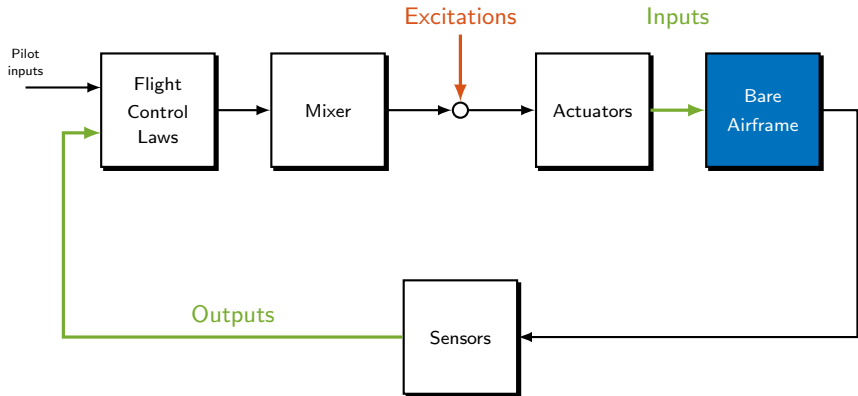


Credit: NASA / Jim Ross

Instrumentation for System Identification



Signals for Bare-Airframe Identification



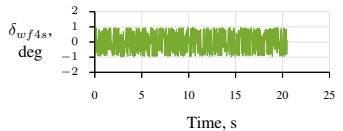
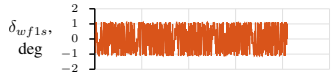
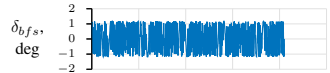
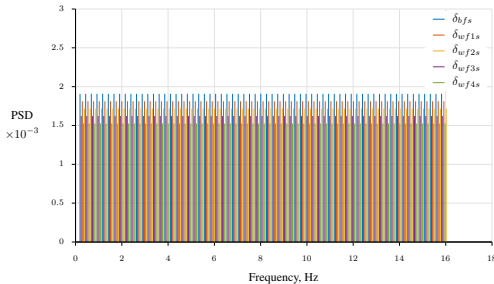
Excitation Design: Multisines [1,2] FTA506

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

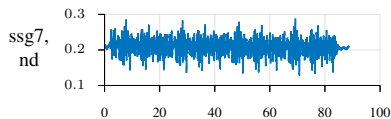
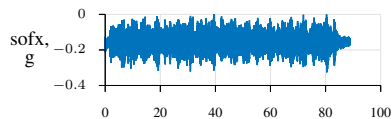
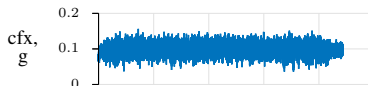
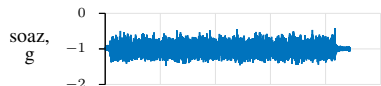
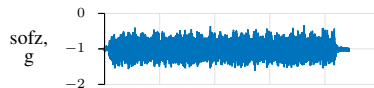
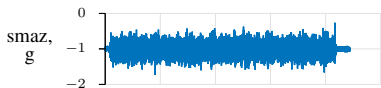
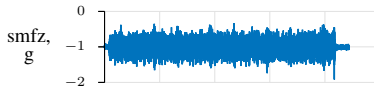
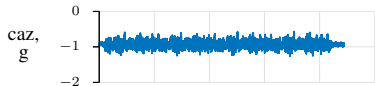
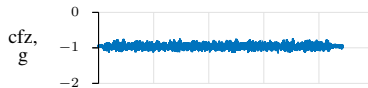
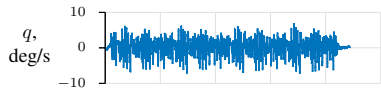
Duration $T = 20.48$ s

Power from about 0.2 to 16 Hz

65 harmonic frequencies per input



Measured Input-Output Data



Time, s

Time, s

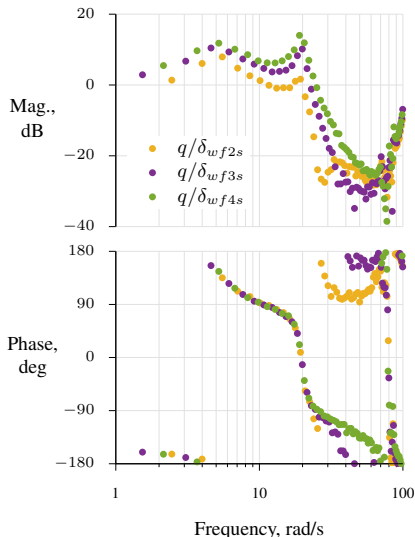
One Approach: Frequency Response Estimation

Difficult because

- Multiple input / multiple output (MIMO) system
- Open-loop dynamics from closed-loop data

$$\mathbf{y}_i(j\omega_k) = \sum_{j=1}^{n_u} \mathbf{G}_{ij}(j\omega_k) \mathbf{u}_j(j\omega_k)$$

Developed an approach for estimating MIMO frequency responses for open-loop systems from closed-loop data when multisines are used [3,4]



Linear Aeroelastic Model Postulation [5–7]

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{\eta} \\ \ddot{\eta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & X_q - w_0 & -g \cos \theta_0 & X_\eta & X_{\dot{\eta}} \\ Z_u & Z_w & Z_q + u_0 & -g \sin \theta_0 & Z_\eta & Z_{\dot{\eta}} \\ M_u & M_w & M_q & 0 & M_\eta & M_{\dot{\eta}} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ Q_u & Q_w & Q_q & 0 & Q_\eta - \omega_n^2 & Q_{\dot{\eta}} - 2\zeta\omega_n \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \eta \\ \dot{\eta} \end{bmatrix} + \begin{bmatrix} X_\delta \\ Z_\delta \\ M_\delta \\ 0 \\ 0 \\ Q_\delta \end{bmatrix} \delta$$

$$\begin{bmatrix} \alpha \\ q \\ a_x \\ a_z \\ \epsilon \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{u_0} & -\frac{x_\alpha}{u_0} & 0 & 0 & \frac{\phi_z}{u_0} \\ 0 & 0 & 1 & 0 & 0 & \nu_\theta \\ A_u & A_w & A_q & 0 & A_\eta & A_{\dot{\eta}} \\ B_u & B_w & B_q & 0 & B_\eta & B_{\dot{\eta}} \\ 0 & 0 & 0 & 0 & \psi & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \eta \\ \dot{\eta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ A_\delta \\ B_\delta \\ 0 \end{bmatrix} \delta$$

* A and B derivatives subsume aerodynamic forces, accelerometer position offset terms, and aeroelastic contributions at the sensor

System Identification using Frequency Responses

Determine the stability and control derivatives (e.g., Z_w , Q_η) that best match the model frequency responses to the frequency response data in a maximum-likelihood sense [1,3,4,8]

$$J(\boldsymbol{\theta}, \mathbf{S}_{vv}) = N \sum_{k=1}^N \mathbf{v}(j\omega_k)^\dagger \mathbf{S}_{vv}^{-1} \mathbf{v}(j\omega_k) + N \ln |\mathbf{S}_{vv}|$$

where

$$\begin{aligned} \mathbf{v}(j\omega_k) &= \text{vec} \left[\mathbf{G}(j\omega_k) - \hat{\mathbf{G}}(j\omega_k) \right] \\ \mathbf{S}_{vv} &= N \mathbb{E} \left[\mathbf{v}(j\omega_k) \mathbf{v}^\dagger(j\omega_k) \right] \end{aligned}$$

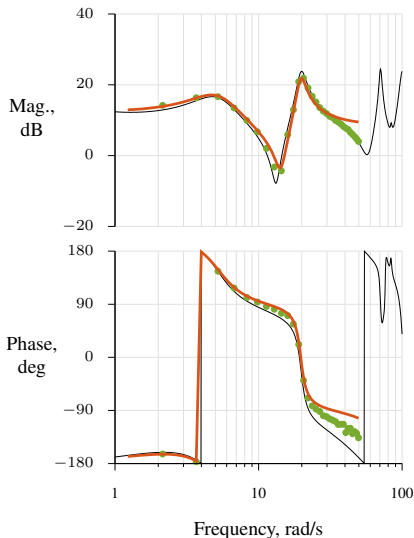
Primarily fitting gyroscope, accelerometer, and strain gauge data

Using the FEM for modal masses, modal frequencies, modal damping ratios, and mode shapes at the sensor locations

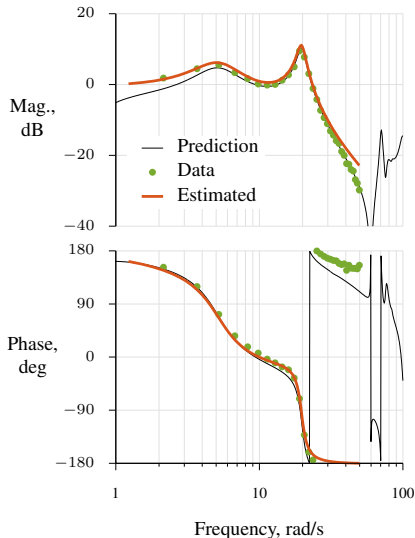
Including effects of sampling, data processing, anti-aliasing filters, etc.

Representative Fits to Modeling Data

$$\frac{1}{2} (a_z^{loa} + a_z^{roa}) / \delta_{wf4s}$$



$$\frac{1}{2} (\epsilon_{11} + \epsilon_{12}) / \delta_{wf4s}$$

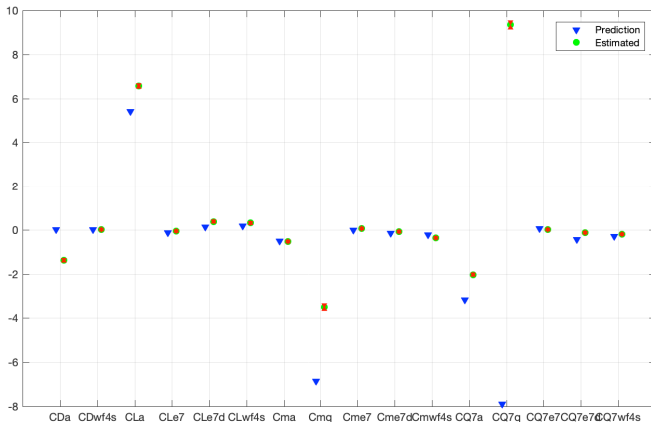




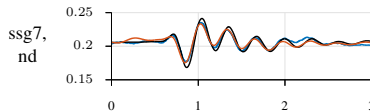
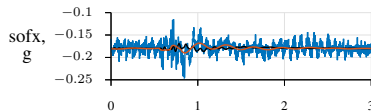
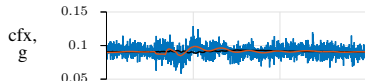
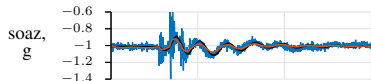
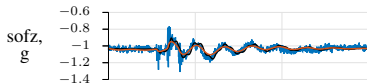
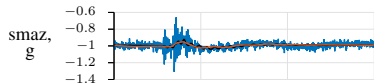
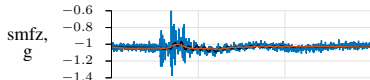
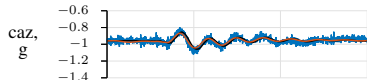
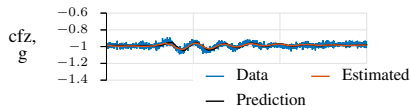
Some Parameter Estimates and Uncertainties

Parameter	Estimate	Standard error	Relative error, %
X_w	$+3.847 \times 10^{-1}$	4.165×10^{-3}	1.1
$X_{\delta_w f 4s}$	-9.284×10^{-1}	5.019×10^{-2}	5.4
Z_w	$-3.374 \times 10^{+0}$	1.076×10^{-2}	0.3
$Z_{\eta 7}$	$+2.795 \times 10^{+0}$	6.760×10^{-2}	2.4
$Z_{\dot{\eta} 7}$	-1.847×10^{-1}	3.582×10^{-3}	1.9
$Z_{\delta_w f 4s}$	$-1.566 \times 10^{+1}$	1.284×10^{-1}	0.8
M_w	-1.385×10^{-1}	8.848×10^{-4}	0.6
M_q	-9.152×10^{-1}	1.153×10^{-2}	1.3
$M_{\eta 7}$	$+1.495 \times 10^{+0}$	9.135×10^{-3}	0.6
$M_{\dot{\eta} 7}$	-2.144×10^{-2}	4.670×10^{-4}	2.2
$M_{\delta_w f 4s}$	$-9.968 \times 10^{+0}$	1.401×10^{-2}	0.1
Q_{7w}	$-2.752 \times 10^{+1}$	1.064×10^{-1}	0.4
Q_{7q}	$+1.263 \times 10^{+2}$	8.769×10^{-1}	0.7
$Q_{7\eta 7}$	$+2.289 \times 10^{+1}$	1.519×10^{-1}	0.7
$Q_{7\dot{\eta} 7}$	$-1.801 \times 10^{+0}$	5.716×10^{-3}	0.3
$Q_{7\delta_w f 4s}$	$-2.769 \times 10^{+2}$	5.016×10^{-1}	0.2

Comparison of Nondimensional Parameters



Prediction using a Validation Maneuver



Time, s

Time, s



Continuing Work

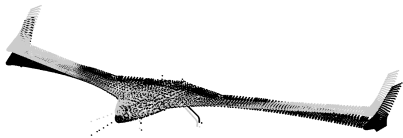
- Include modes 9 (first wing torsion, SW1T) and 10 (symmetric wing fore-aft, SFA) into the identification
- Include additional measurements into the identification
- Repeat the identification using output error parameter estimation with Fourier transform data
- Go through the flight envelope



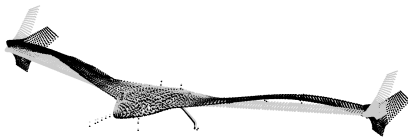
References and Further Reading

1. Morelli, E., and Klein, V., "Aircraft System Identification: Theory and Practice," 2nd edition, Sunflyte Enterprises, Williamsburg, VA, 2016.
2. Grauer, J., and Boucher, M., "System Identification of Flexible Aircraft: Lessons Learned from the X-56A Phase 1 Flight Tests," AIAA Atmospheric Flight Mechanics Conference, 2020, doi: 10.2514/6.2020-1017.
3. Grauer, J., and Boucher, M., "Real-Time Estimation of Bare-Airframe Frequency Responses from Closed-Loop Data and Multisine Inputs," *Journal of Guidance, Control, and Dynamics*, vol. 43, No. 2, February 2020, doi: 10.2514/1.G004574.
4. Grauer, J., and Boucher, M., "Aircraft System Identification from Multisine Inputs and Frequency Responses," *Journal of Guidance, Control, and Dynamics*, vol. 43, No. 12, December 2020, doi: 10.2514/1.G005131.
5. Waszak, M., and Schmidt, D., "Flight Dynamics of Aeroelastic Vehicles," *Journal of Aircraft*, Vol. 25, No. 6, June 1988, doi: 10.2514/3.45623.
6. Schmidt, D., "Modern Flight Dynamics," McGraw-Hill, New York, NY, 2011.
7. Grauer, J., and Boucher, M., "Output Measurement Equations for Flexible Aircraft Flight Dynamics," NASA TM-2018-220102, October 2018.
8. Klein, V., "Aircraft Parameter Estimation in Frequency Domain," AIAA Atmospheric Flight Mechanics Conference, 1978, doi: 10.2514/6.1978-1344.

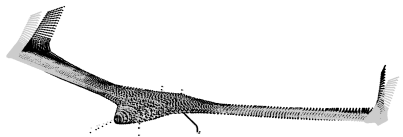
Mode Shapes from the FEM



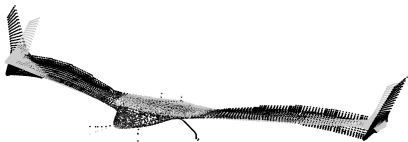
Mode 7 — Symmetric wing 1st bending (SW1B)



Mode 9 — Symmetric wing 1st torsion (SW1T)



Mode 10 — Symmetric wing fore-aft (SFA)



Mode 14 — Symmetric winglet lateral (SWL)