System Identification - Theory and Practice

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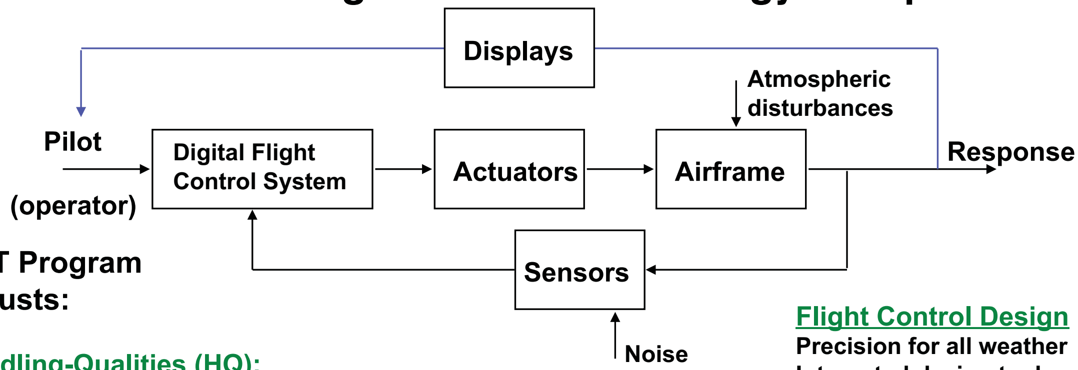
Outline

- AFDD flight control technology group and key design tools
- Background on system identification
- Key roles for flight simulation and flight control development
- Demonstration of CIFER®
- Questions

AFDD Flight Control Technology Group



S&T Program Thrusts:

Handling-Qualities (HQ):
Reqmts (JHL/JMR)
Limited authority
Envelope limiting
Flight test techniques

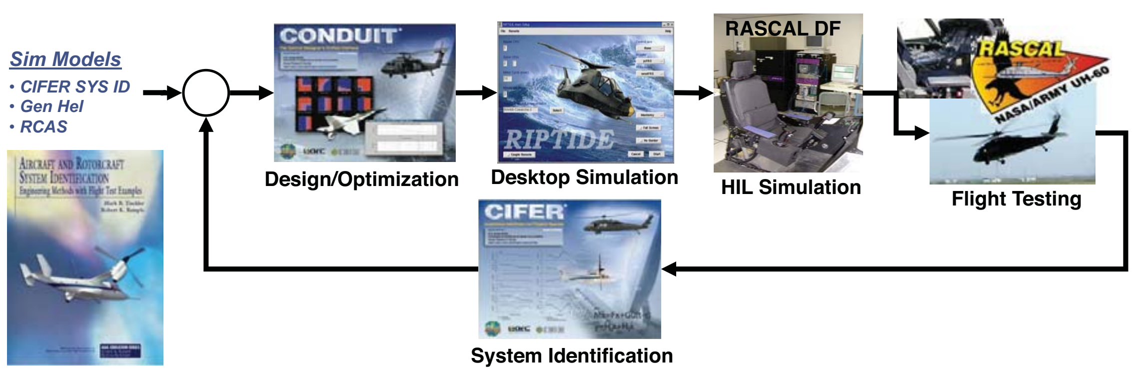
Modeling Methods:
Physics-based models
Simulation validation/improvement
Higher-order linear models
System identification

Flight Control Design
Precision for all weather
Integrated design tools
Advanced rotor controls
UAV autonomy

Advanced Sensors
Display formats/dynamics
Blade motion sensors
Obstacle sensing

Flight-Test Applications
Upgrades of Army fielded systems: AH64, CH47F, UH-60 FBW
AFDD flight assets: UH-60 sling-load, RASCAL full-authority FBW, Autonomous RMAX
Cooperative efforts with industry: CH53X, FireScout, ARH)

Rapid Desktop-to-Flight Development Pathway



Applications:

- Improved handling qualities of new and current aircraft
- UAV control laws with any level of autonomy or cooperation
- Advanced system control modes (INav&FC) and displays (HMDs)
- Hardware-in-the-loop (HIL) simulation and on-board-monitoring
- Basic launch platform for evaluating advanced concepts

=> Successfully applied to CH-47F DAFCS, AH-64D MCLAWS, CH-53X, UH-60M, ARH, Fire Scout, improving accuracy and speed of design

AFDD Design Tool Application

Background

- **What is aircraft system identification?**

  - Determination of a mathematical description of aircraft dynamic behavior from measured aircraft motion

Assumptions → **Model** → **Simulation** → **Predicted Aircraft Motion**

Physical Understanding ← **Model** ← **System Identification** ← **Measured Aircraft Motion**

- **What are system identification results used for?**

  - **Wind tunnel vs. flight test measured characteristics**
  - **Simulation model development / validation**
  - **Subsystem hardware/software modeling**
  - **HQ specification compliance**
  - **Optimization of automatic flight control systems**

- **What are the special problems that arise in applying system ID to aircraft?**

- High level of measurement noise
- High order of dynamical system
- High degree of inter-axis coupling
- Unstable vehicle dynamics

Nonparametric and Parametric Modeling

- **Nonparametric modeling: no model structure or order is assumed**

  - frequency-response (frequency-domain)

  Bode plot format: Log-mag (db) and phase (deg) of input-to-output ratio vs. freq.

  Applications: bandwidth, time-delay, pilot-in-the-loop analysis, math model validation, parametric model structure and order

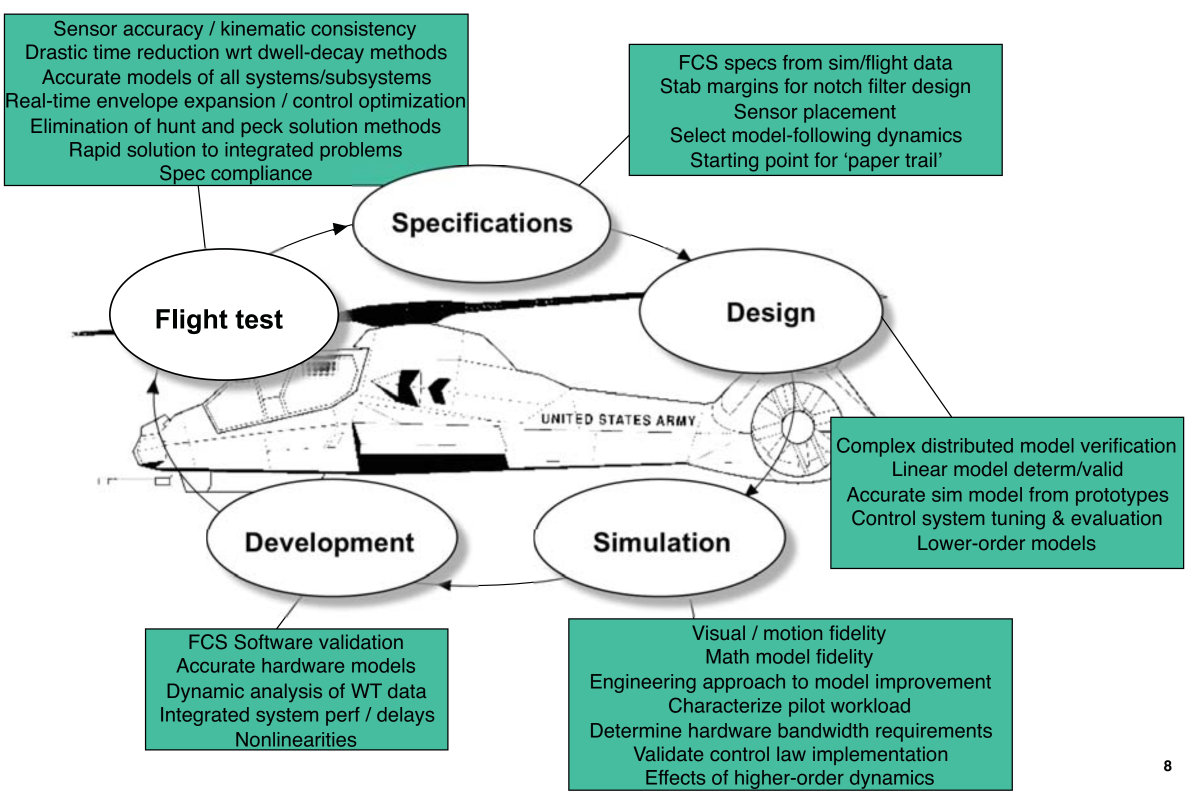
- **Parametric modeling: model order and structure must be assumed**

  - transfer-function: pole-zero representation of individual freq. response pairs

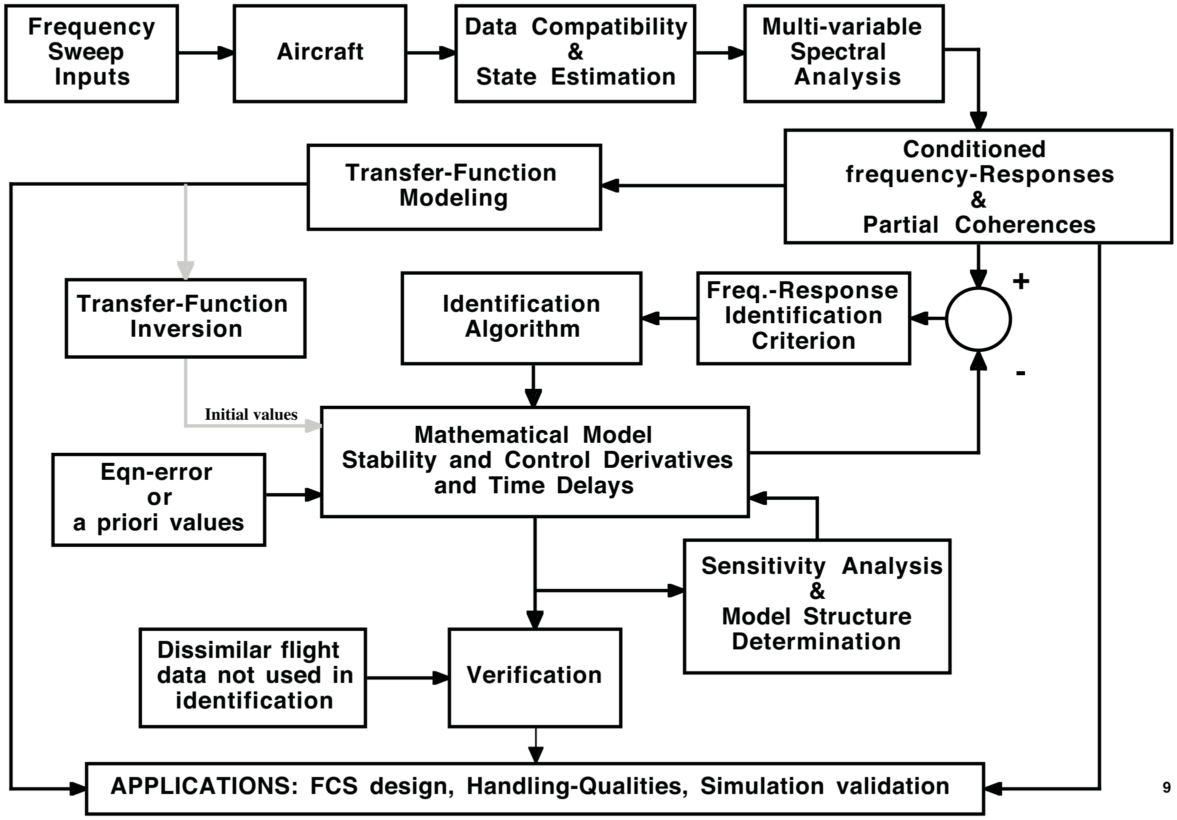
  - state-space description: aerodynamic stability and control derivative representation

  Applications: control system design, wind-tunnel and math model validation

How will SID Support the Development Process?



Frequency-Response Method for System ID



Key Features of Frequency-Response Approach for System Identification

• Frequency-response calculation eliminates uncorrelated process and output measurement noise effects:

Frequency-response: $$\hat{H} = \frac{G_{xy}}{G_{xx}}$$

• Parametric models are obtained by matching the nonparametric frequency-response in frequency-range where the data is most accurate:

Coherence: $$\widehat{\gamma^2_{xy}} = \frac{|G_{xy}|^2}{|G_{xx}|\,|G_{yy}|}$$

• Time delays can be identified directly:

$$\Phi = -\omega\,\tau$$

Frequency-Response Method Features (Cont)

- Number of unknowns greatly reduced relative to time-domain solution

$$\dot{x} = Fx + Gu(t-\tau) + bias$$

$$y = Hx + ju(t-\tau) + yref$$

$$T(s) = (H[sI-F]^{-1}G + j)\, e^{-\tau s}$$

6 dof model:

number of unknowns in F, G, tau = 64
time-domain soln: 8 bias terms + (9 outputs x 4 records) = 44 extra terms

- Data points in cost function greatly reduced relative to time-domain soln
  => Well suited to identification of coupled rigid body/structural dynamics

- Applicable to identification of unstable systems
  => TD integration errors make this very difficult for long data records.

Frequency-Domain SID Methods are Especially Well-Suited to Flight Control System Development and Validation

- Well suited to complex problems:
  - Multiple overlapping modes, unstable systems, low signal-to-noise
- Frequency-responses are nonparametric characterizations obtained without first determining state-space model structure
- Broken-loop & closed-loop responses provide important “paper trail”
- Feedback stability and noise amplification determined from broken-loop frequency-response => crossover freq., gain/phase margins, PSD
- Command tracking based on end-to-end closed-loop response
  => bandwidth, phase delay, and lower-order equiv. systems

Payoffs:

✳ HQ/AFCS/Vib testing accounts for 37% of all flight testing

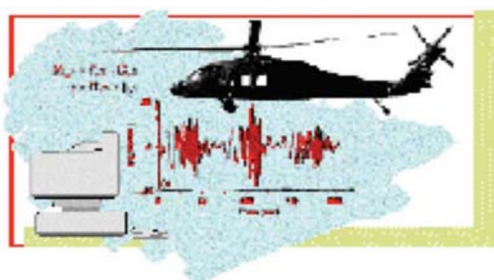
(Ref. Crawford, “Potential for Enhancing the Rotorcraft Development / Qualification Process using System Identification,” RTO SCI Symposium on System Identification for Integrated Aircraft Development and Flight Testing,” 5-7 May 1998, Madrid, Spain.)

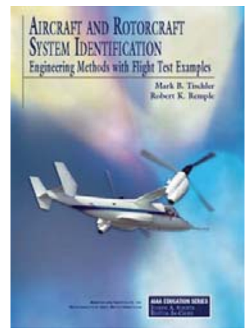
✳ Modern FBW flight test programs cost approx. $50K/flight-hr

CIFER®
Comprehensive Identification from FrEquency Responses

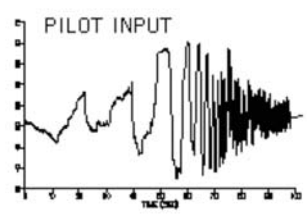
Key features of the CIFER® approach are:

- **Integrated databasing and screen-driven commands**
- **Unique ID and analysis algorithms highly-exercised on many flight projects (r/c and fixed-wing)**
- **MIMO frequency-response solution**
- **Highly-flexible and interactive definition of ID model structures.**
- **Very reliable, systematic, and integrated model structure procedure**
- **Integrated model verification in the time-domain**





Frequency-Domain SID Maneuvers



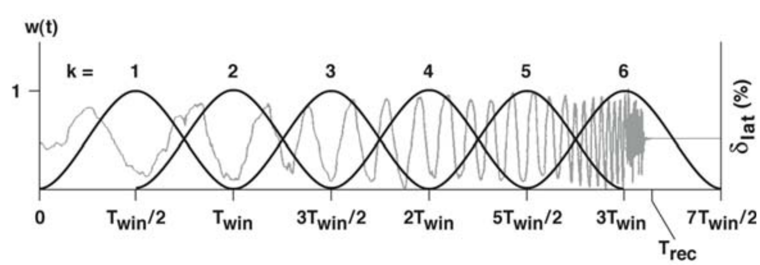
- Identification maneuver: Frequency-Sweep
  - Well suited to freq.-domain SID
  - Even distribution of spectral content
  - Input and output are roughly symmetric
  - Frequency-range is strictly controlled during test
  - Very safe and well established method.

- Verification maneuver: Doublet
  - Characteristic of realistic pilot input
  - Symmetric response keeps aircraft within flight condition used in the SID tests
  - Different form than sweeps - guards against overtuning of identification

Instrumentation Requirements for Aircraft Application

- **Sample rate:**
  - All signals at same sample rate and filtering
  - Desired rate is 25x modes of interest
    - » 50 hz for rigid body response
    - » 100 hz for structural response to 4 hz
- **Piloted control inputs**
- **Aerosurface deflections**
- **SAS command inputs**
- **Aircraft response:**
  - Alpha, beta
  - p, q, r
  - Phi, theta
  - ax, ay, az
- **Structural response:**
  - Wing tip accelerometers
  - Fuselage accelerometers

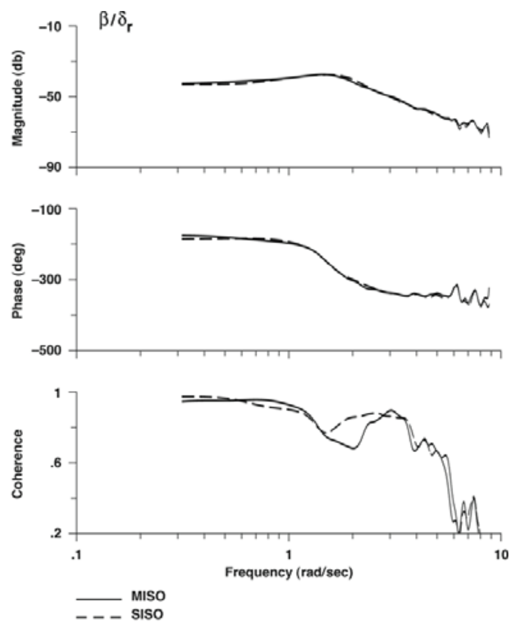
Overlapped Averaging

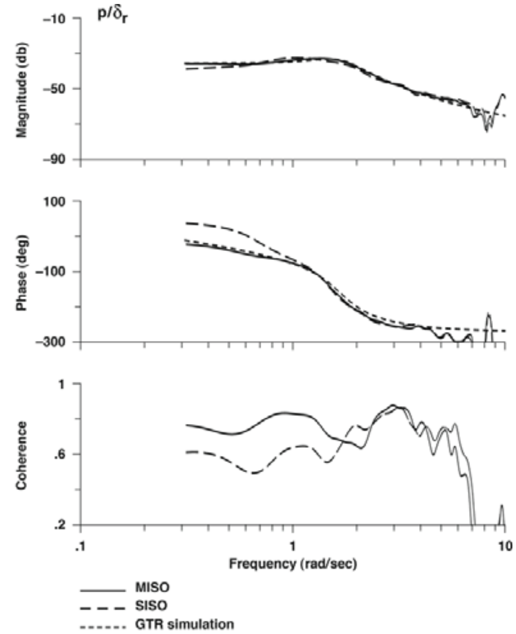


- **Chirp z Transform allows FFT over freq. Range of interest with flexibility and high resolution**
- **Random error is inversely proportional to sqrt of # of windows**

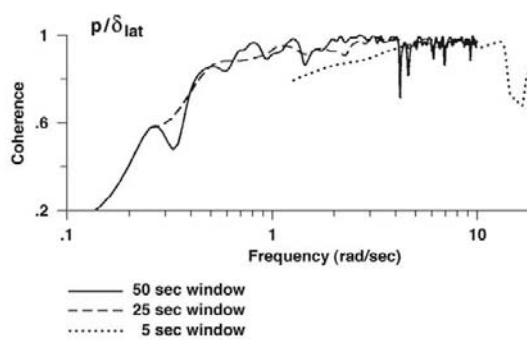
Importance of Multi-Input Solution for Coupled System ID

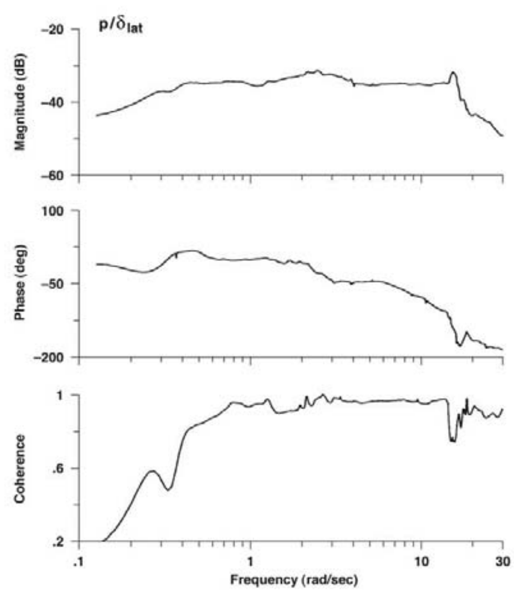
$$\frac{y_j}{x_i}(f) = \frac{G_{x_i y_j}}{G_{x_i x_i}} \neq \boldsymbol{G}^{-1}{}_{xx}(f)\boldsymbol{G}_{xy}$$





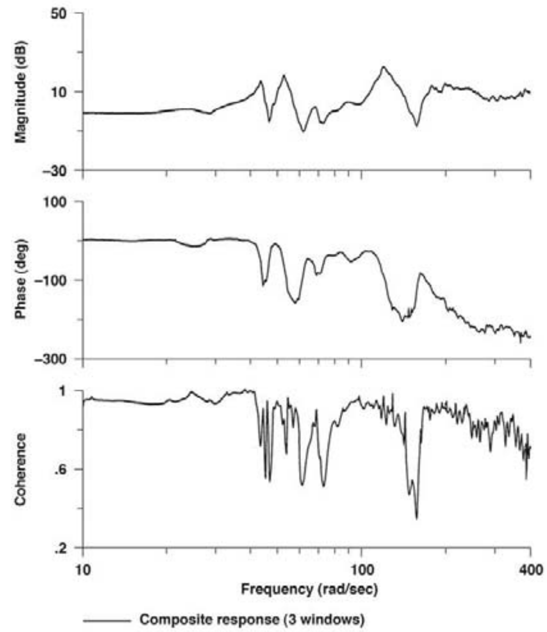
Composite Window Averaging





- **Final composite frequency-response ID has exceptional accuracy and dynamic range**

COMPOSITE Window Especially Important for Structural Response ID



Frequency-Response Matching Procedure

- The state-space model is formulated in general as:

$$M_m \dot{x} = F_m x + G_m u$$
$$y = H_m x + j_m u$$

The elements of M_m , F_m , G_m , H_m , j_m are the unknown s&c derivatives
=> some elements may be known from physical considerations or TF models

- Taking Laplace transform:

$$T_m(s) = H_m [sI - M_m^{-1} F_m]^{-1} M_m^{-1} G_m + j_m$$

- Incorporate a matrix of time delay functions $\tau_m(s)$ and eliminate j_m by allowing H_m to be a function of s:

$$T_m(s) = H_m(s) [sI - M_m^{-1} F_m]^{-1} M_m^{-1} G_m \tau_m(s)$$

Frequency-Response Cost Function

The unknown parameters (state-space matrices) are determined by minimizing the
weighted cost function J:

$$J(\Theta) = \sum_{n=1}^{n_\omega} \varepsilon^T(\omega_n,\Theta)\, W\, \varepsilon(\omega_n,\Theta)$$

$\omega_1, \omega_2, \ldots, \omega_{n_\omega}$ **: freq. points for each input/output pair; range is selected based on individual range of good coherence and overall applicability of model structure**

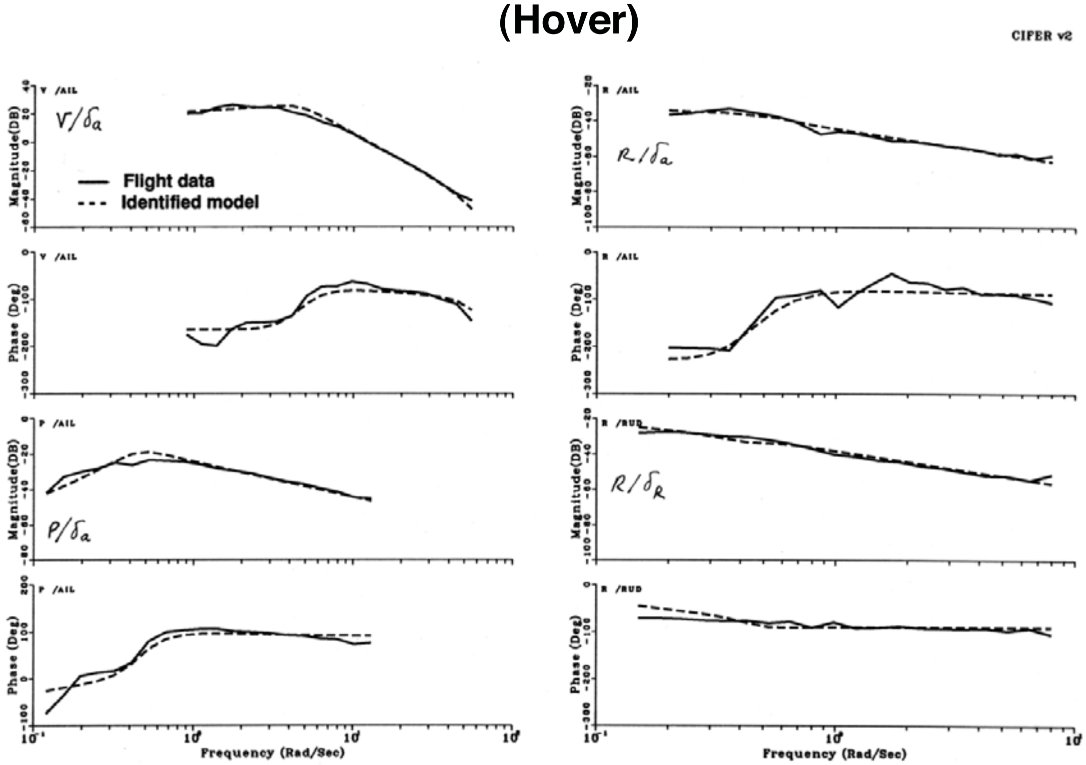
e **: vector of magnitude and phase errors between the identified MISO (composite) frequency-responses T(s) and the model responses** $T_m(s)$

W: weighting function at each freq. and for each FR pair; comprised of:

- **relative magnitude / phase weighting (nominal: 7.57 deg: 1dB)**
- **coherence weighting**

=> Nonlinear minimization using Secant pattern search to find (local) minimum of J

Stability and Control Derivative Model ID (Hover)



XV-15 Tilt-Rotor Identification Results (Hover)

$$\dot{x} = Fx + Gu$$
$$y = Hx + ju$$

F-matrix

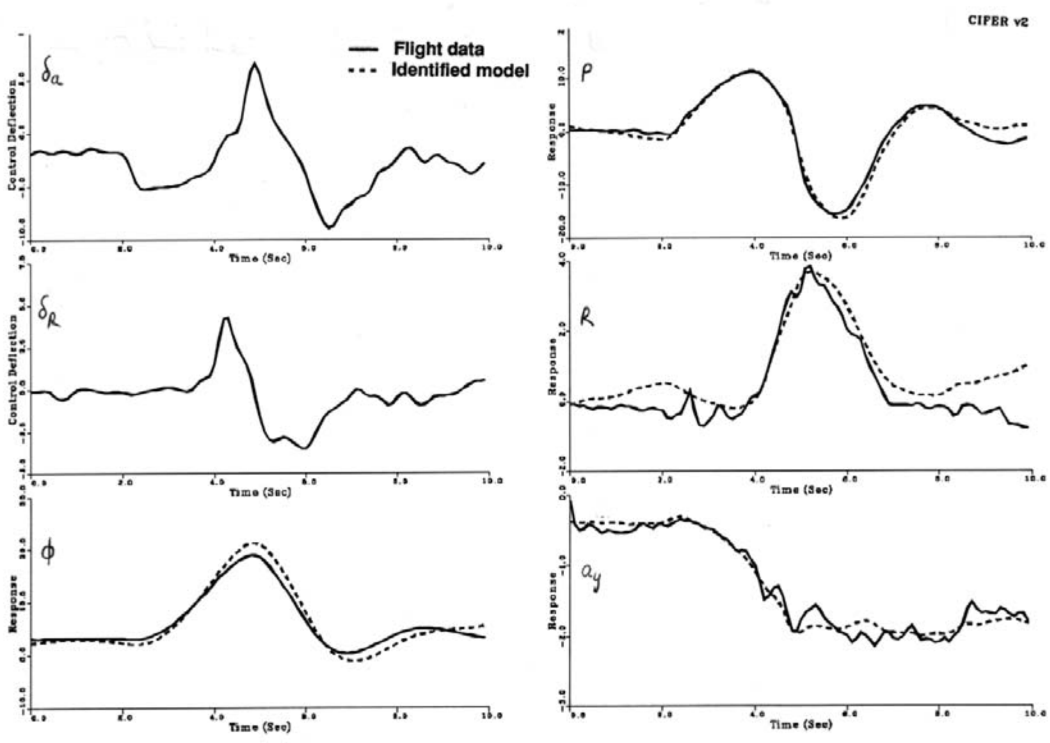
	XVMOD4	
Derivative	Param Value	C.R. (%)
Y_v	-0.1102	6.271
Y_p	-1.422	12.46
Y_r	0.000 +	.....
G	32.17 †	.....
L_v	-3.775E-03	6.084
L_p	-0.2775	15.64
L_r	-0.8726	13.17
N_v	6.337E-04	7.425
N_p	0.02914	30.20
N_r	0.000 +	.....
K_{in}	1.000 †	.....

G-matrix

	XVMOD4	
Derivative	Param Value	C.R. (%)
Y_{δ_a}	-0.04584	5.925
Y_{δ_r}	0.000 +	.....
L_{δ_a}	-0.06094	3.039
L_{δ_r}	0.000 +	.....
N_{δ_a}	5.909E-03	4.802
N_{δ_r}	0.01238	4.650
τ_{ail}	0.000	.....
τ_{rud}	0.000	.....

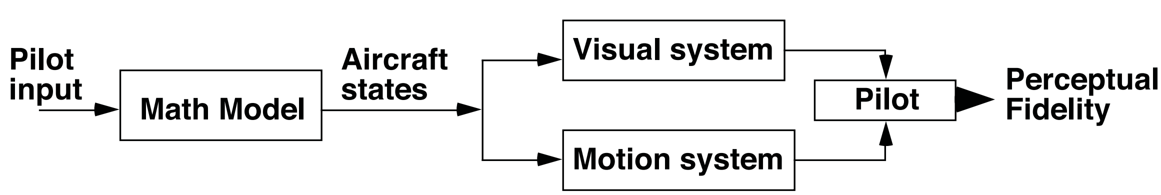
+ Eliminated during model structure determination

Verification of State-Space Model (Hover)



Key Roles of CIFER System ID for Flight Simulation

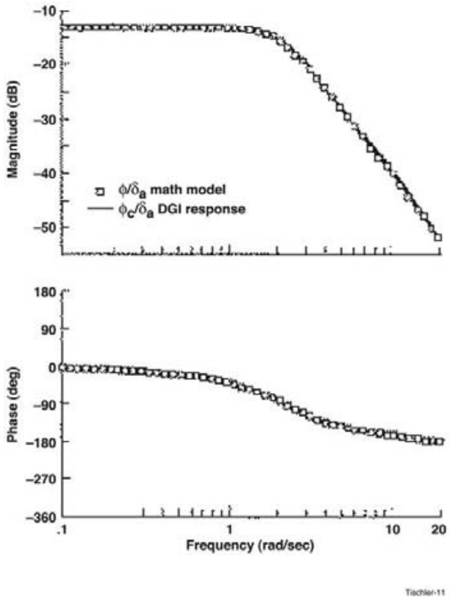
Simulation Components



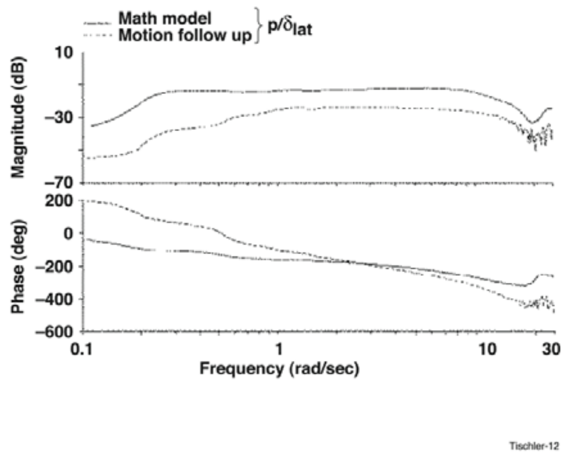
=> Perceptual fidelity: end-to-end frequency response

Validation of Simulator Visual and Motion Systems
(VMS, Ames)

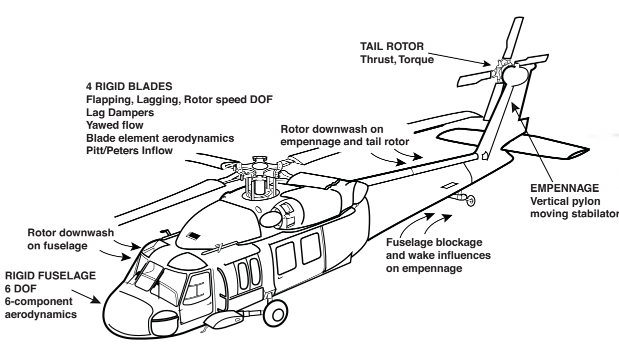
Visual System Response
Includes McFarland Compensation



Motion System Response



Component Type Model
(GenHel)



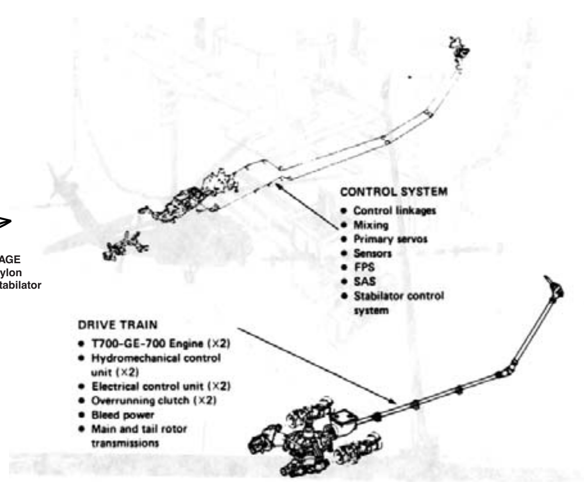


Fig. 1. Sikorsky-Ames Gen Hel UH-60 real-time simulation model.

Verification of Simulation Dynamics

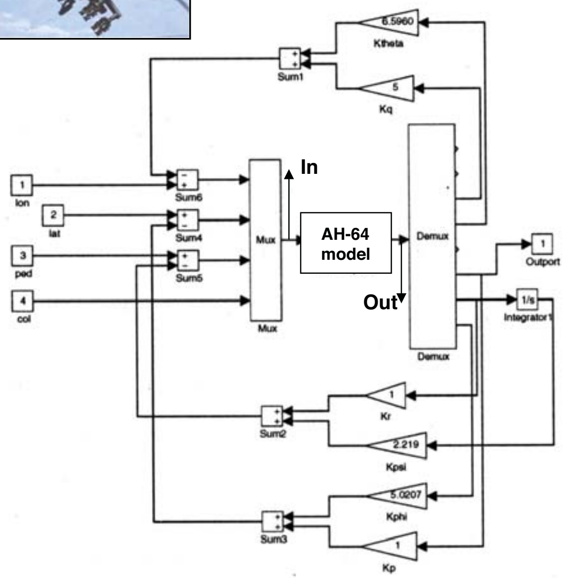


Figure 3: Feedback loops to maintain attitude during frequency sweep

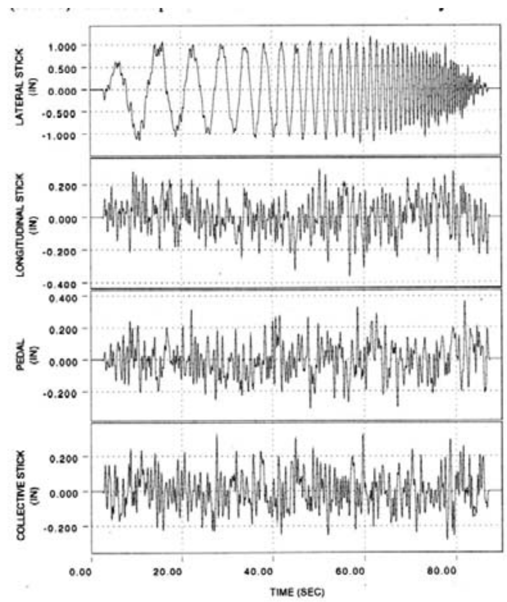
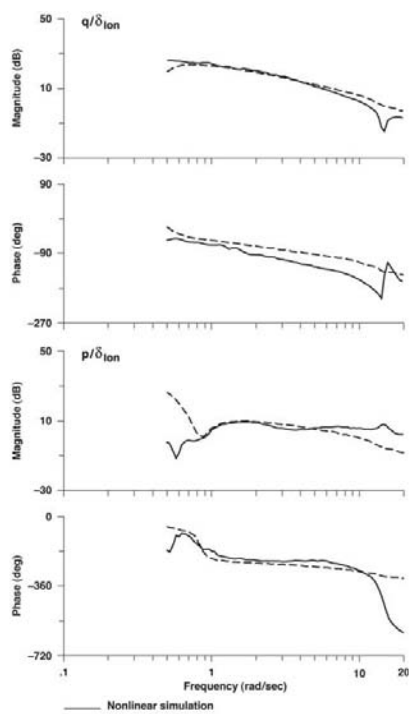


Figure 2: Typical computer generated frequency sweep input including white noise

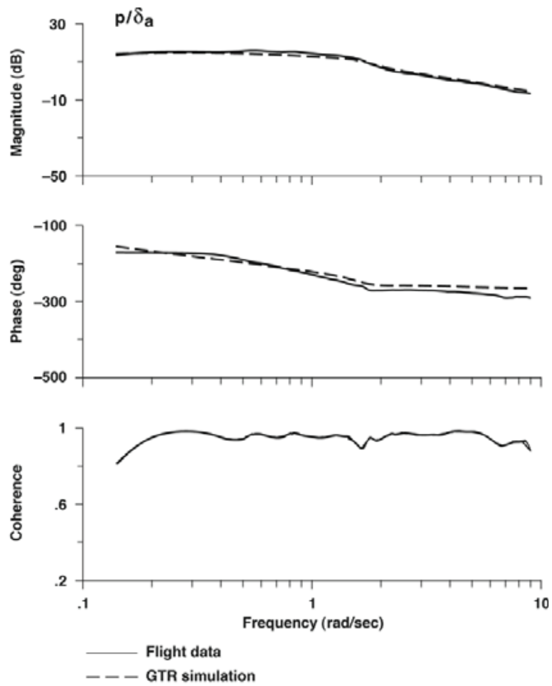
Ref: H. Mansur and M. Tischler, "An Empirical Correction Method for Improving Off-Axis Response in Flight Mechanics Helicopter Models," AHS Journal Vol 43, No. 2, April 1998.

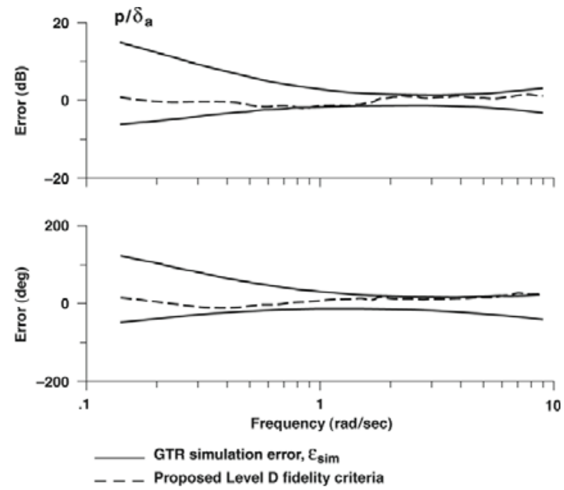
Comparison of Higher-Order Nonlinear Response with 6DOF Perturbation (LINMOD) Model



Excellent means to validate distributed model dynamics and linearization methods

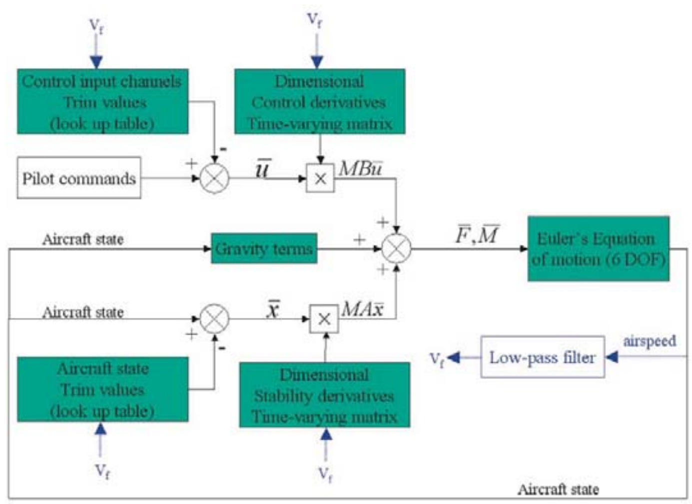
Simulation Model Fidelity Assessment (XV-15 cruise)



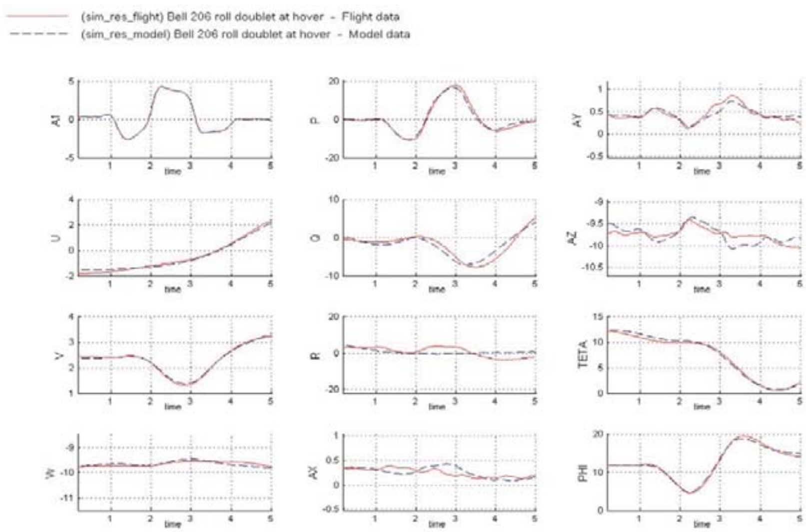


Simulation meets simulation fidelity criteria

Block Diagram for Full Envelope Simulation Model from ID Results (IAI Bell 206)



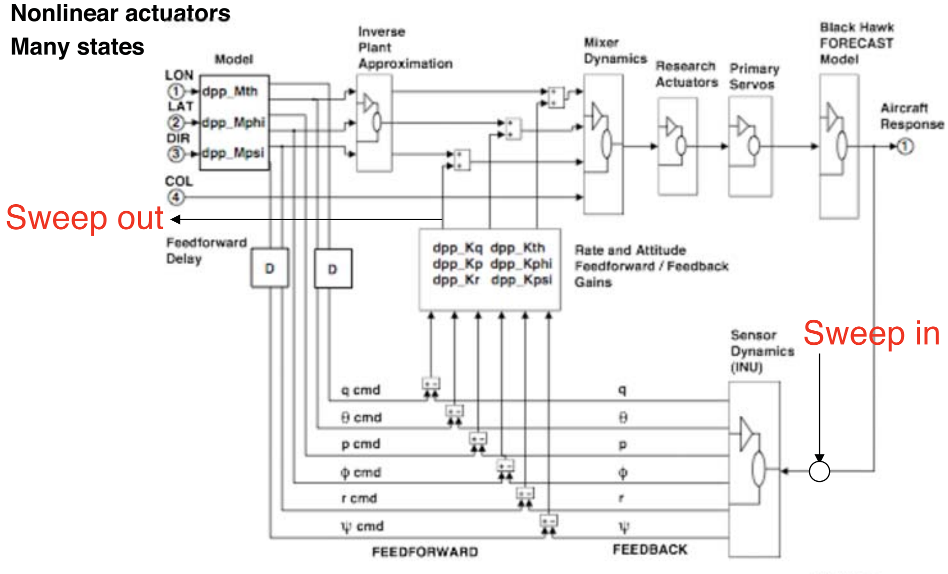
Full Envelope Simulation Model from ID Results
(IAI Bell 206)



• Efficient and very accurate approach to developing piloted/engineering sim

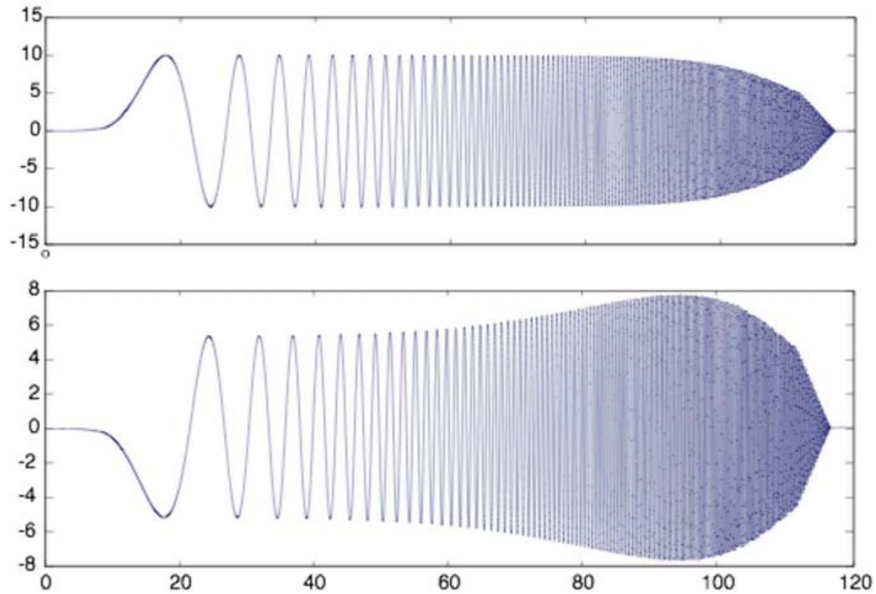
Simulink Model Validation

- **Full RASCAL control laws**
- **Nonlinear actuators**
- **Many states**



Extraction of linearized (perturbation) model from SIMULINK model using "LINMOD" function is often inaccurate
=> control system design will not respond as expect in flight.

Computer Generated Sweep



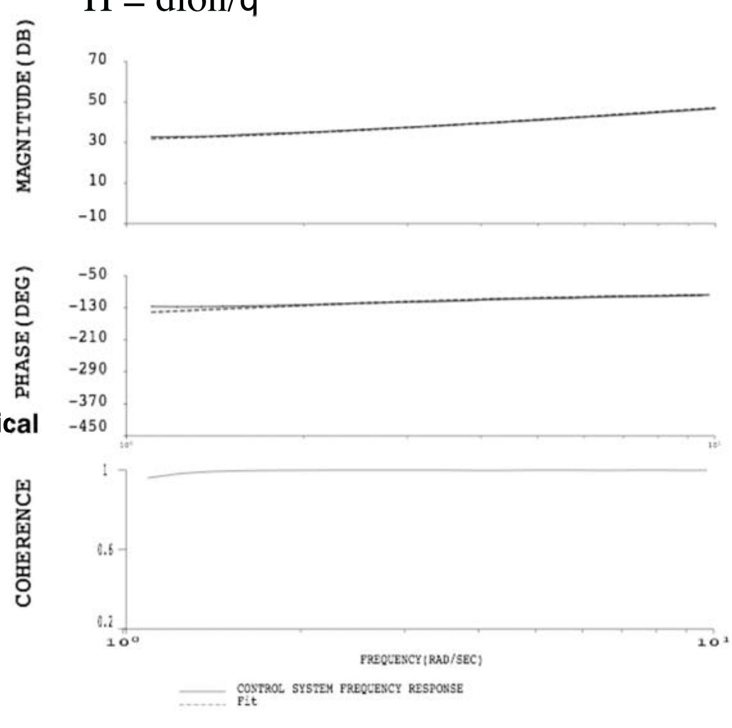
Validation of SAS Implementation and Linmod

H = dlon/q

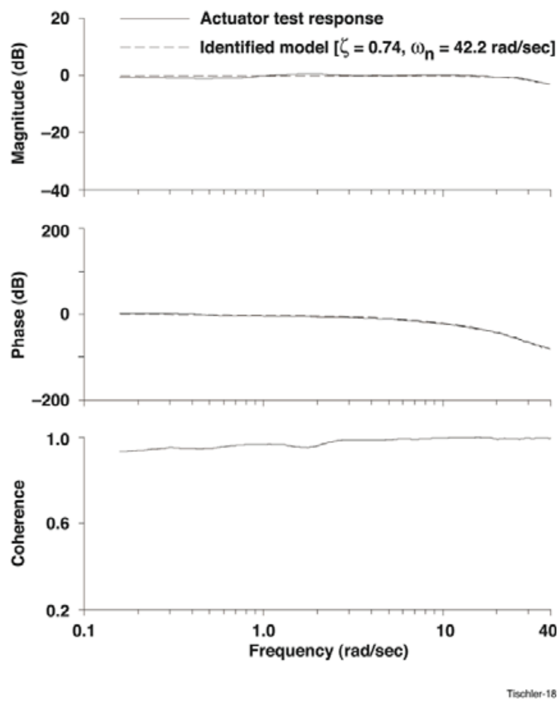
- **Transfer-Function Fit:**
  H_q = - 22.5 (s+1.37)
  = - 22.5 s - 30.8
  = - Kq s - K_q

- **Analytical gains:**
  K_q = 21.5 (4%)
  K_q = 32.8 (7%)

- **Small differences due to numerical integration and nonlinearities**

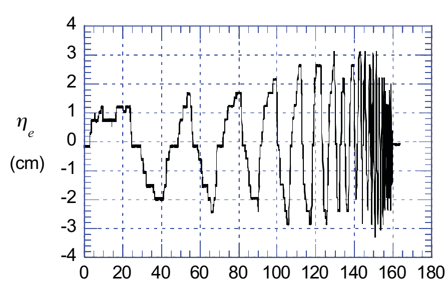


Actuator Response Determination from Bench Tests



Closed-Loop Handling-Qualities -- TU 144
(M=1.9)

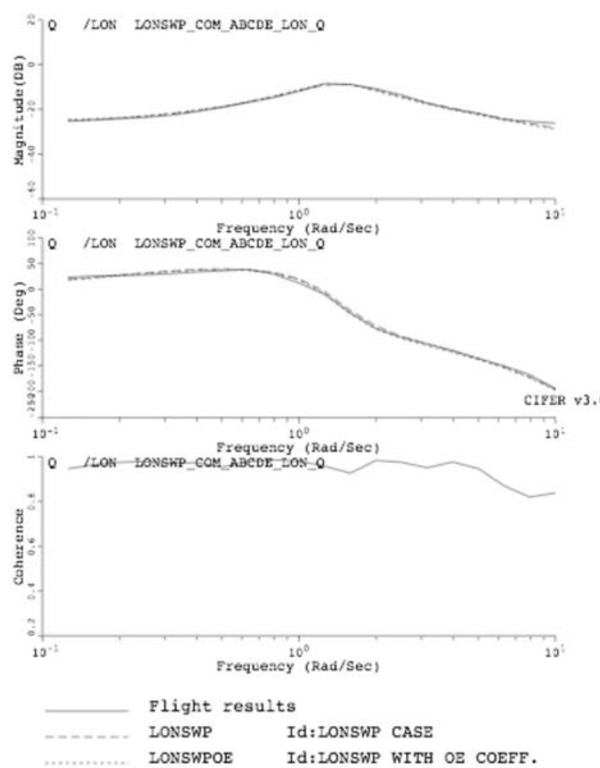
Piloted frequency-sweeps



- **LOED Short period dynamics:**

$$\frac{q}{\delta_e} = \frac{K_\theta (1/T_{\theta_2}) e^{-\tau_\theta s}}{[\zeta_{sp}, \omega_{sp}]}$$

Excellent agreement of LOES models (OE and CIFER) with frequency response data



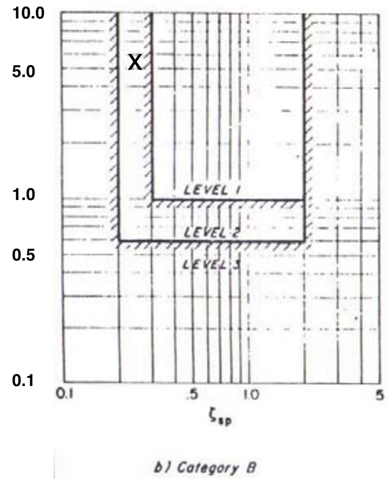
Ref: E. A. Morelli, AIAA-2000-3902, AFM, Aug, 2000, Denver, Co.

LOES Results From Sweep (M=1.9)

Parameter	*EE/OE Estimate (Std. Error)*	*CIFER Estimate (% error)*
b_1	*0.353 (0.011)*	*0.380 (5.8%)*
b_0	*0.106 (0.006)*	*0.1072 (12.32%)*
a_1	*0.932 (0.035)*	*1.040 (11.61%)*
a_0	*1.970 (0.035)*	*2.103 (6.3%)*
τ_e	*0.194 (0.014)*	*0.192 (6.9%)*
$1/T_{\theta_2}$	*0.30*	*0.28*
ζ_{SP}	*0.33*	*0.36*
ω_{SP}	*1.40*	*1.45*

Cat B (gradual maneuvering)

$\omega_{sp}T_{\theta_2}$



Excellent agreement of results for two ID approaches (OE and CIFER) for this simple (rigid body) model

HQ Parameters

$\zeta_{sp} = 0.36$

$\omega_{sp} = 1.45\,r/s$

$\omega_{sp}T_{\theta_2} = 5.18\,rad$

Time Delay Limits

Level 1: t < 0.10

Level 2: t < 0.20

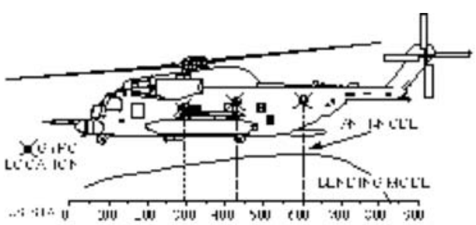
Level 3: t < 0.30

=> Level 2 handling-qualities

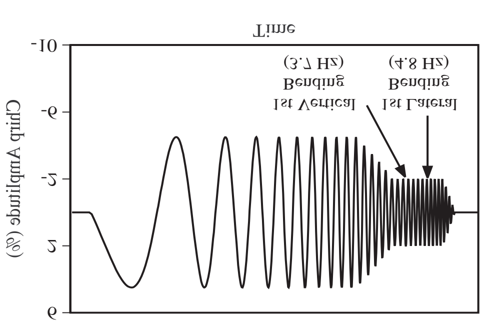
Ref: E. A. Morelli, AIAA-2000-3902, AFM, Aug, 2000, Denver, Co.

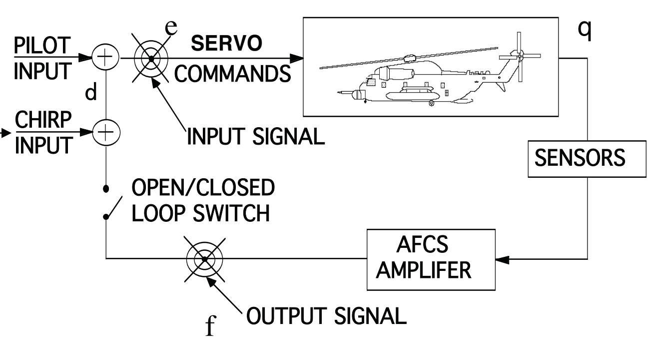
MH53J Servo-Elastic Test Program

Sensor locations



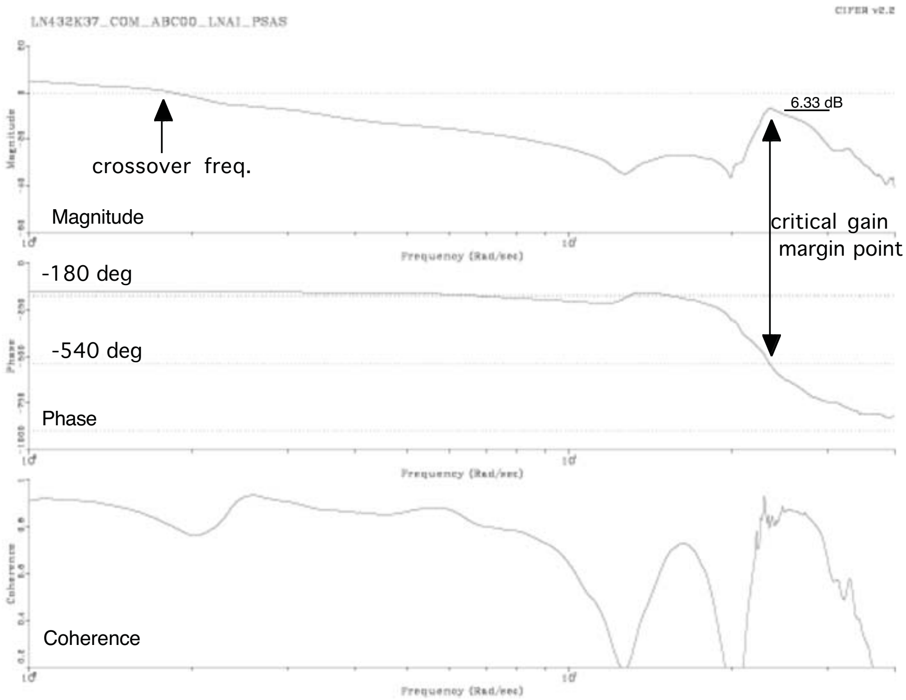
- **Stability margin: direct calculation: f(s) / e(s)**
- **Handling-qualities: (1/s)[q(s)/d(s)]**





Ref: Crawford, "Potential for Enhancing the Rotorcraft Development / Qualification Process using System Identification," RTO SCI Symposium on System Identification for Integrated Aircraft Development and Flight Testing," 5-7 May 1998, Madrid, Spain.

MH53J Stability Margin Results



Cross. freq. = 1.9 r/s
PM = 30 deg.

Crit. Freq (rad/sec)	Gain Margin (db)
7.1	16.9
12.8	33.8
15.6	26.2
23.5	6.3

XV-15 Flutter Envelope Clearance Testing

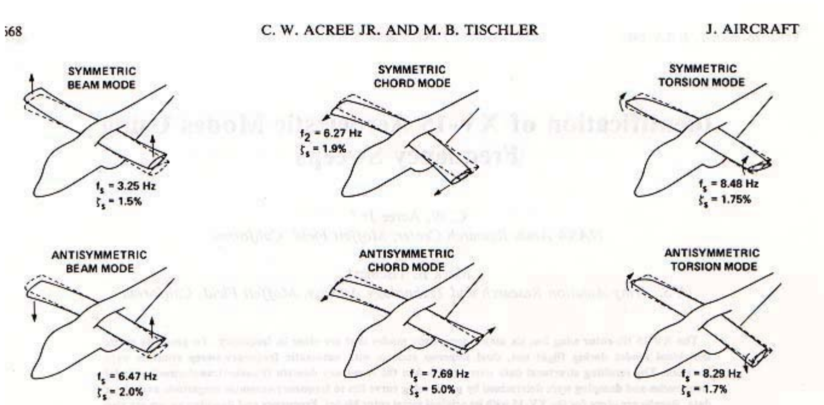


Fig. 2 XV-15 wing modes, with structural frequencies and damping.

Ref: C. Acree, M. Tischler, "Identification of XV-15 Aeroelastic Model Using Frequency Sweeps," Journal of Aircraft, Vol 26, No. 7, July 1989, pg 667-674.

Modal Identification

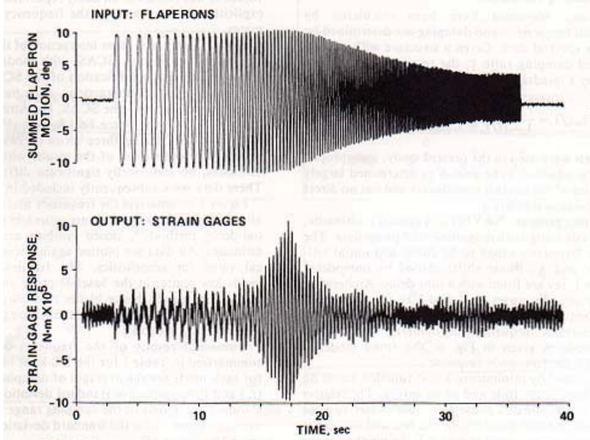


Fig. 5 Input and output time histories for one symmetric flaperon sweep (beam mode).

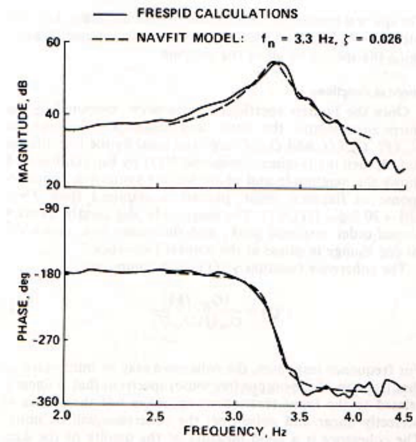
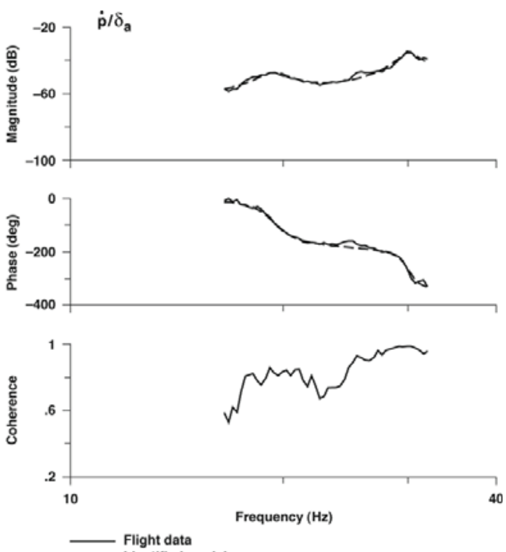
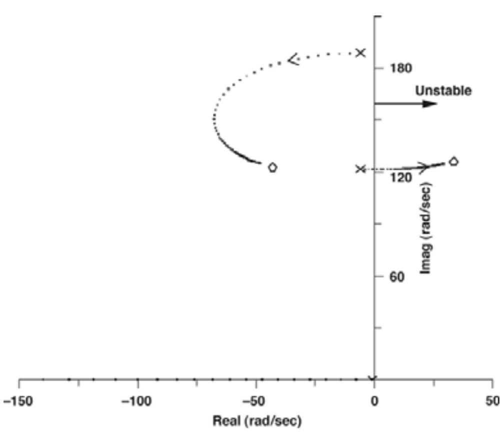


Fig. 6 Symmetric beam mode frequency response and fitted second-order model.

•Sum and difference processing of symmetric measurements significantly improves signal/noise

Coupled Rigid Body/Structural ID
(AV-8B Harrier)

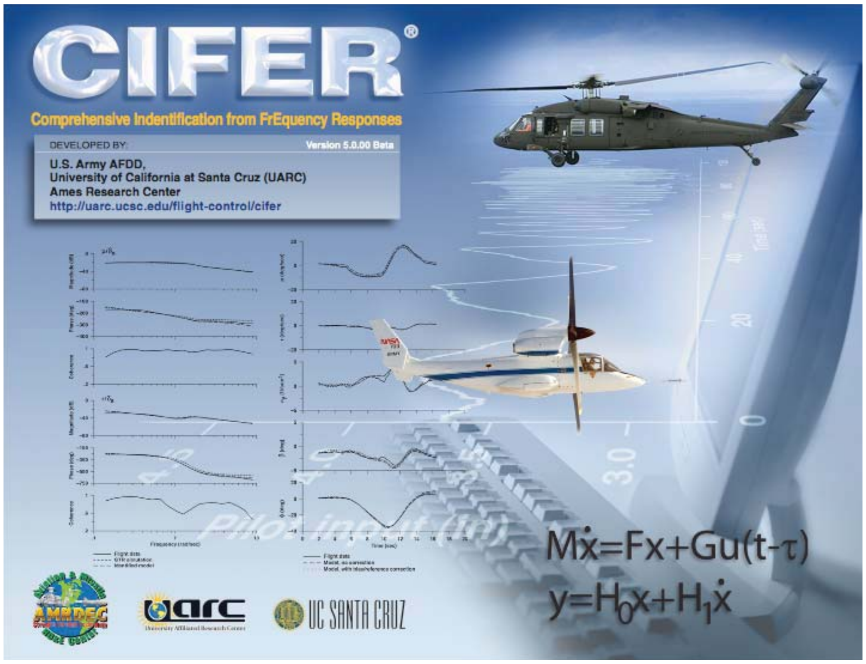




$$\frac{p}{\delta_a} = \frac{L_{\delta_a}}{(s - L_p)} + \frac{K_1 s}{[s^2 + 2\zeta_1 \omega_{n_1} s + \omega_{n_1}^2]} + \frac{K_2 s}{[s^2 + 2\zeta_2 \omega_{n_2} s + \omega_{n_2}^2]} + \cdots$$

$[\zeta_1 = 0.049;\ \omega_{n_1} = 19.4\text{ Hz}]$ $[\zeta_2 = 0.031;\ \omega_{n_2} = 30.1\text{ Hz}]$

Demonstration of CIFER®



Questions ?