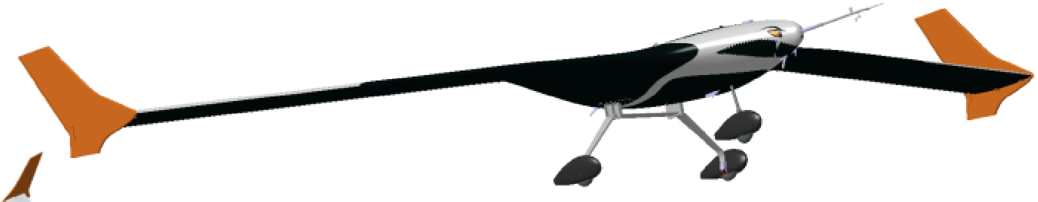
X-56A MUTT

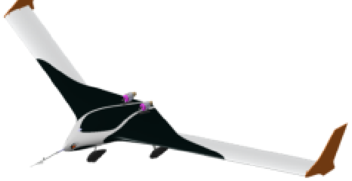
Aeroservoelastic Modeling

Background
X-56 MUTT

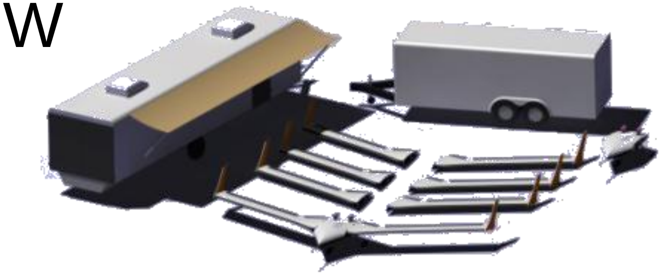
2 Center Bodies
1 Stiff Wing Set
3 Flexible Wing Sets
1 Ground Control Station

- With Simulation and SIL Capabilities





28 Ft Span
480 lb GTOW
150 Knots
10,000 ft



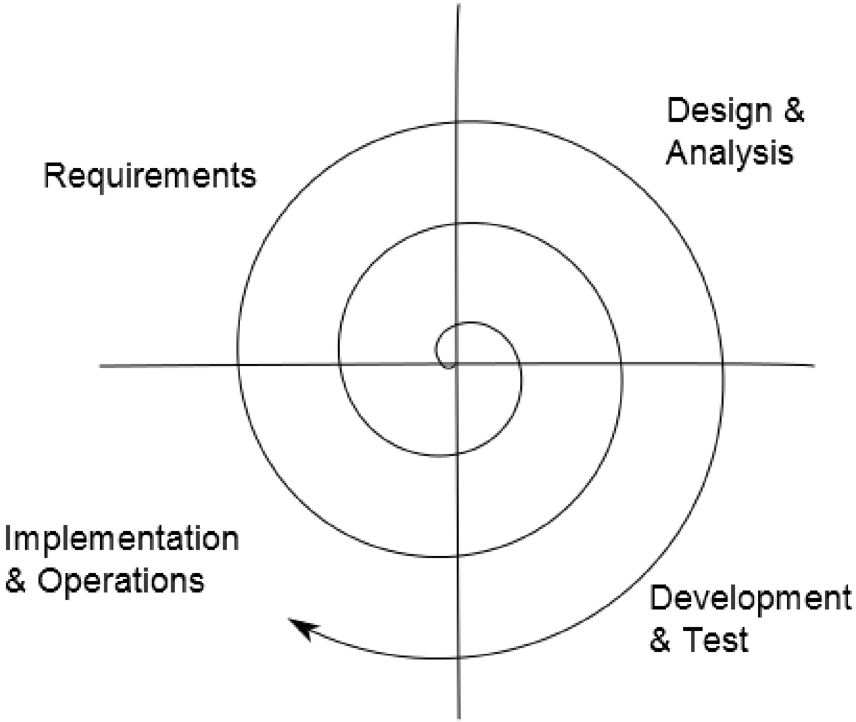
X-56 Modeling Overview

- Nonlinear Piloted Simulation
  - Currently only rigid body dynamics
    - Limited to stiff wing
  - High fidelity
    - Nonlinear aerodynamics, freeplay, etc.
  - Usage
    - Aircrew training
    - Failure modes and effects testing
    - Yaw control

- Linear NDoF Models v7.030
  - High order
  - Accurate model of aeroelastic dynamics
  - Usage
    - Control law design
    - Control law analysis
    - Design of programed test inputs

NDoF Model Development

- Stiff Wing
  - Development of the modeling methodology
    - Identical approaches used for both wing sets
    - Only differences is finite element parameters
  - V&V of modeling methodology
    - Validation of stiff wing models is validation of flex wing models
    - Calibration of rigid body parameters directly applicable to flex wings
  - Refinement of model requirements
- Flex Wing
  - Prediction of body freedom flutter
  - Demonstration of flutter suppression



Spiral Development Model (Boehm)

Modeling and Simulation

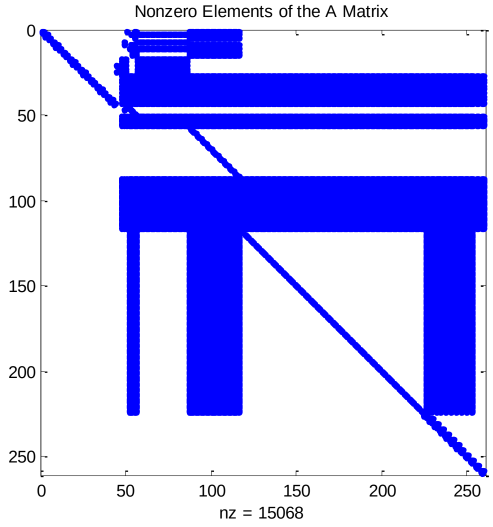
SYSTEM & ANALYSIS FRAMEWORK

Modeling Approach

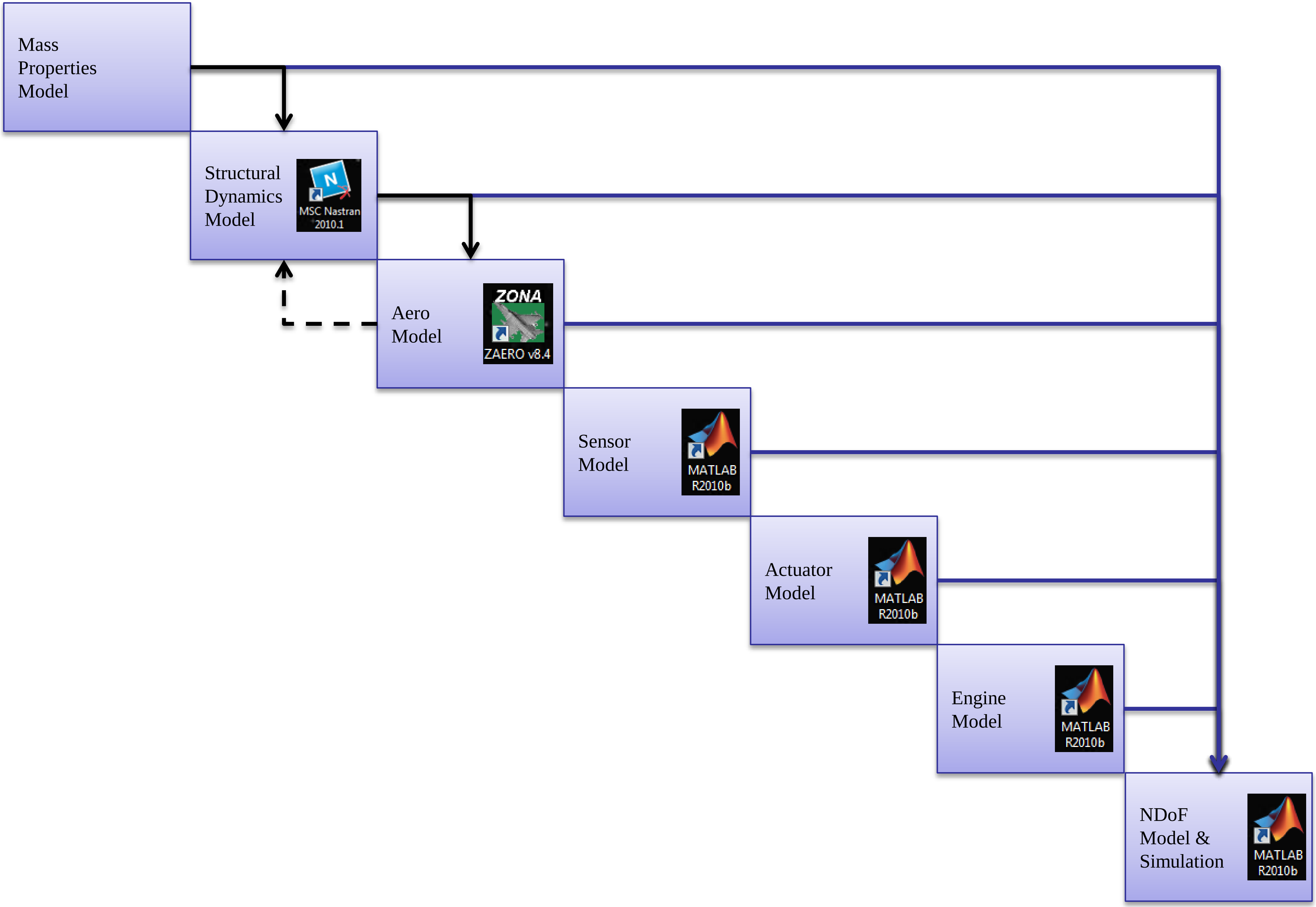
- Linear NDoF Models
  - 260 Total States
    - 6 Rigid Body Modes
    - 30 Elastic Modes
      - 2 states each
    - 108 Aerodynamic Lag States
    - 44 Sensor States
    - 36 Actuator States
  - Models at discrete flight conditions
    - Airspeed
    - Fuel Weight
  - Updated with data from nonlinear simulation
    - Sensor Dynamics and Noise
    - Tuned wind tunnel aerodynamic data
    - Weight and Balance

$$\begin{Bmatrix}\dot{x}_s\\ \dot{x}_{fd}\\ \dot{x}_\xi\\ \dot{x}_{act}\end{Bmatrix} = \begin{bmatrix} A_s & C_r & C_e & 0 & D_{sc}\\ 0 & A_{rr} & A_{re} & D_r & B_{rc}\\ 0 & A_{er} & A_{ee} & D_e & B_{ec}\\ 0 & E_r & E_e & R & E_c\\ 0 & 0 & 0 & 0 & A_{act}\end{bmatrix}\begin{Bmatrix}x_s\\ x_{fd}\\ x_\xi\\ x_{act}\end{Bmatrix} + \begin{bmatrix}0\\ 0\\ 0\\ 0\\ B_{act}\end{bmatrix}\{u\}$$

Variable	Description
x_s	Sensor States
x_{fd}	Rigid Body (Flight Dynamic) States
x_ξ	Elastic (Structural) States
x_{act}	Actuator States



Modeling Architecture (N^2 Chart)



Mass Properties Model

Structural Dynamics Model

Aero Model

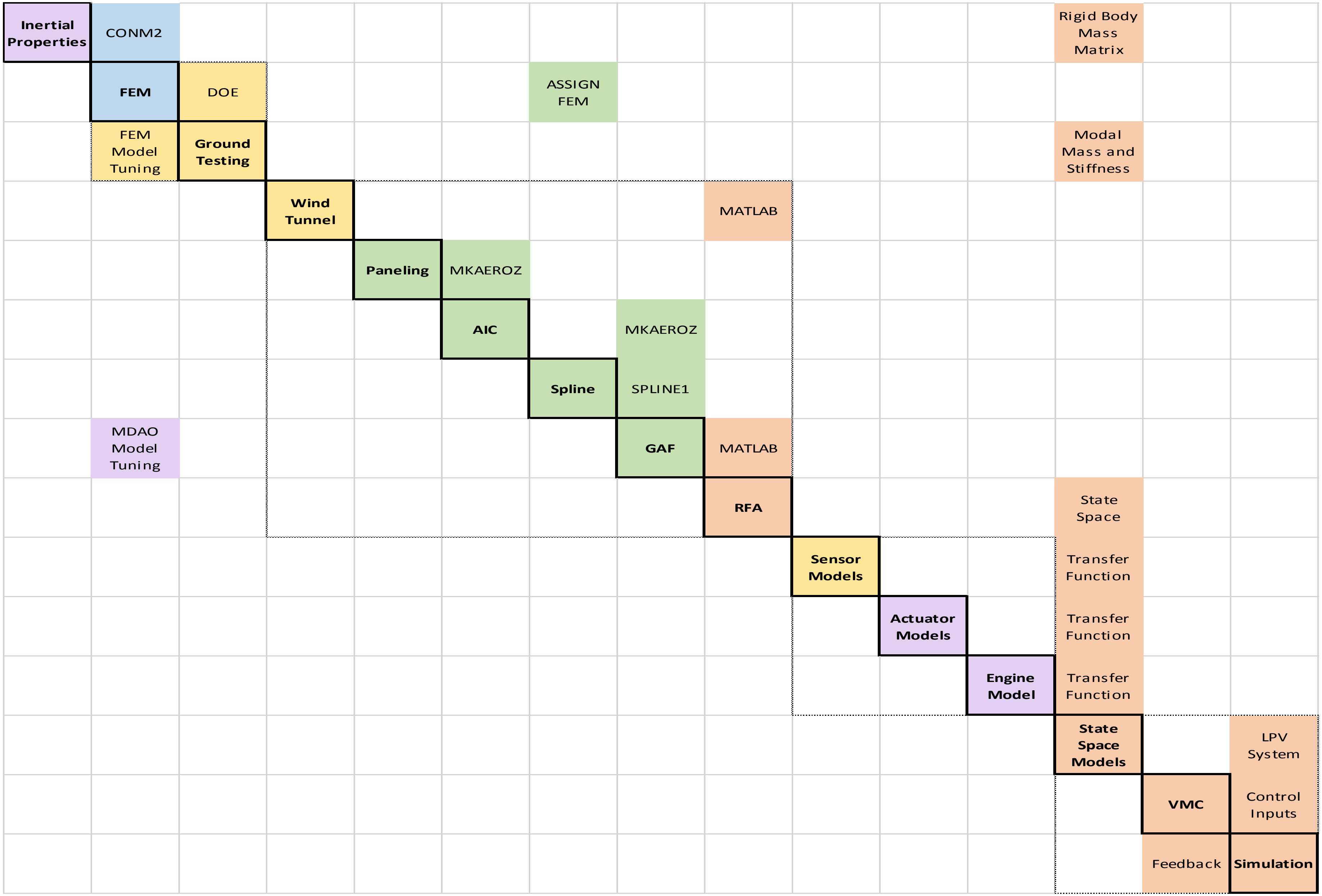
Sensor Model

Actuator Model

Engine Model

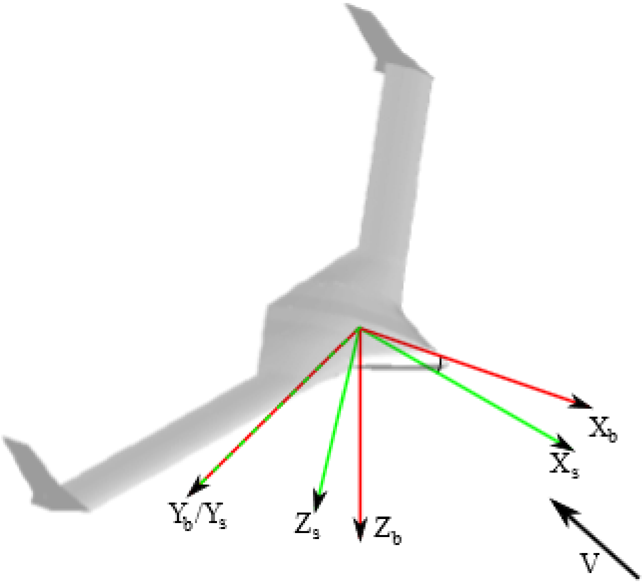
NDoF Model & Simulation

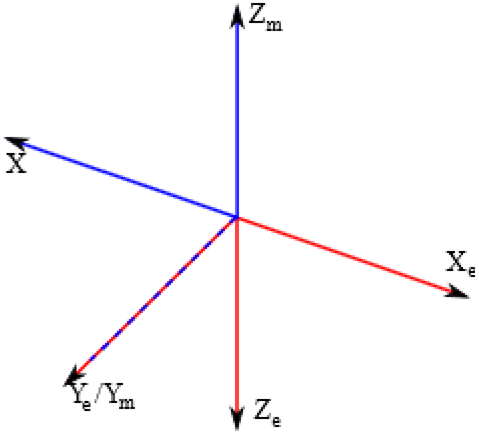
Detailed N^2 Chart



Inertial Properties	CONM2											Rigid Body Mass Matrix		
	FEM	DOE				ASSIGN FEM								
	FEM Model Tuning	**Ground Testing**										Modal Mass and Stiffness		
			Wind Tunnel					MATLAB						
				Paneling	MKAEROZ									
					AIC		MKAEROZ							
						Spline	SPLINE1							
	MDAO Model Tuning						**GAF**	MATLAB						
								RFA				State Space		
									Sensor Models			Transfer Function		
										Actuator Models		Transfer Function		
											Engine Model	Transfer Function		
												State Space Models		LPV System
													VMC	Control Inputs
													Feedback	**Simulation**

- **Stability Axis**
  - Non-inertial coordinate system
  - Used for aerodynamic loads
- **Body Axis**
  - Non-inertial coordinate system
  - Nonlinear simulation equations of motion
- **Modal Coordinate**
  - Inertial coordinate system
  - Used in structural model
  - ZAERO’s aerodynamic model
  - X & Z flipped from earth fixed coordinates
  - Structural dynamics orthogonal to rigid body dynamics
- **Earth Fixed**
  - Inertial coordinate system
  - Flat earth



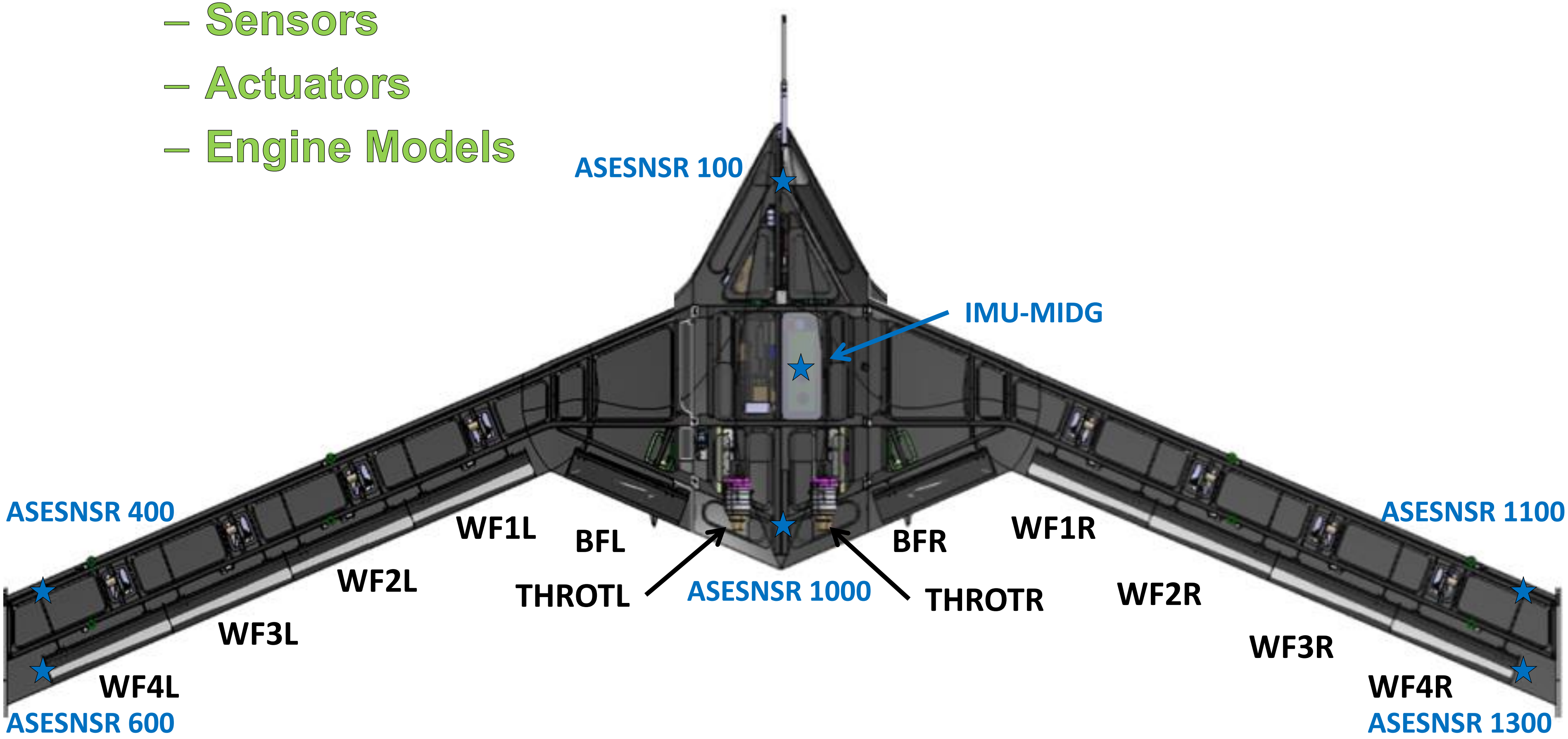


Modeling and Simulation

NDOF MODEL SUBSYSTEMS

Model Components

- ASE Modeling Components
  - Inertial Properties
  - Structural Models
  - Aerodynamics
  - Sensors
  - Actuators
  - Engine Models

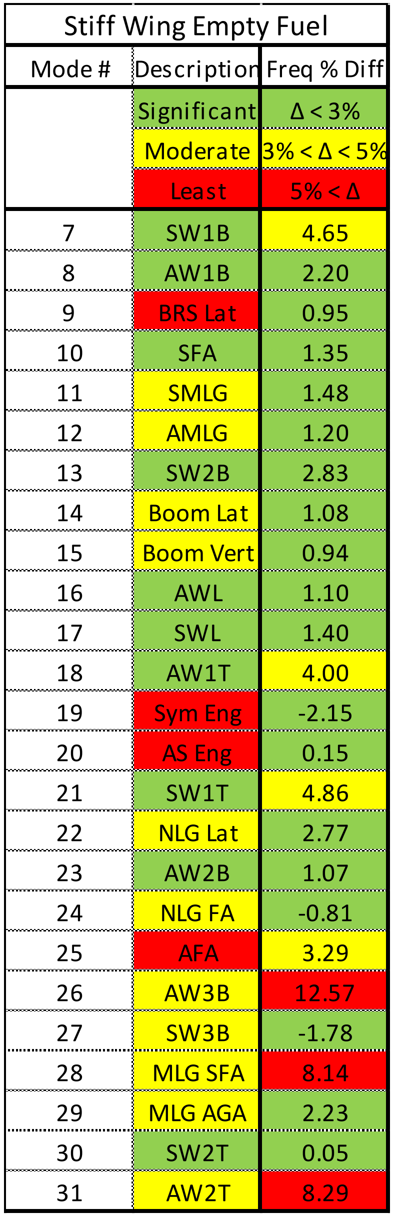


Inertial Properties

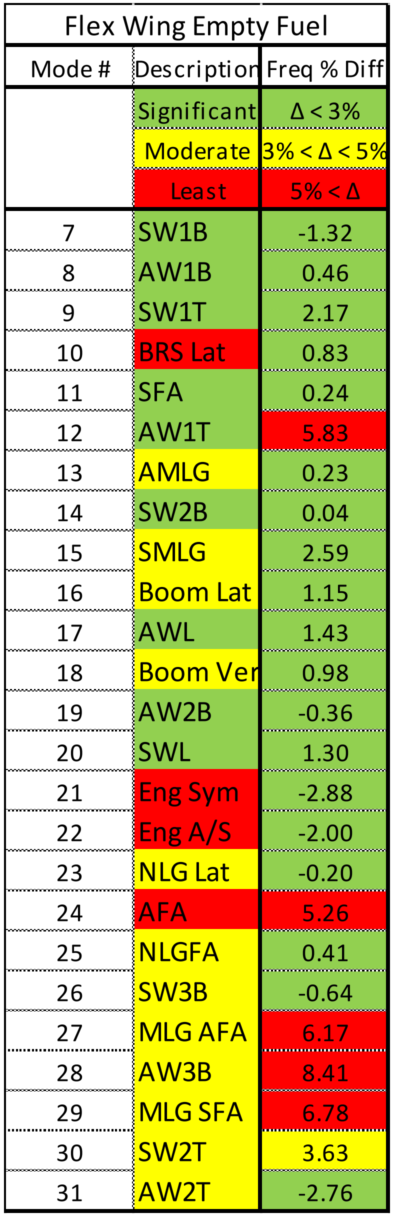
- Rigid Body Inertia
  - From Lockheed Martin nonlinear simulation
  - Measured values in piloted simulation
- NASA weight and balance
  - Center of Gravity
  - Fuel mass
- Structural Mass Properties
  - More detailed distribution required for structural dynamics
  - Modeled in NASTRAN finite element model
  - Validation
    - Rigid body portions similar to measured values on Fido
    - Modal assurance criteria tested in GVT

Structural Model Validation

- Lockheed Martin FEM
  - Stiff Wing v09
    - Updated with centerbody from flex wing v10
  - Flex Wing v10
- Structural Coupling Test
  - Excitation by control surface inertia
  - Fido and Buckeye have similar structural dynamics

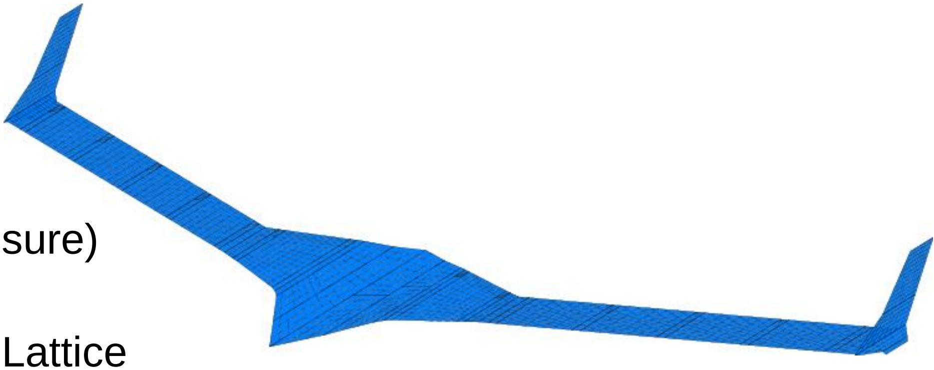


Stiff Wing Empty Fuel		
Mode #	Description	Freq % Diff
	Significant	Δ < 3%
	Moderate	3% < Δ < 5%
	Least	5% < Δ
7	SW1B	4.65
8	AW1B	2.20
9	BRS Lat	0.95
10	SFA	1.35
11	SMLG	1.48
12	AMLG	1.20
13	SW2B	2.83
14	Boom Lat	1.08
15	Boom Vert	0.94
16	AWL	1.10
17	SWL	1.40
18	AW1T	4.00
19	Sym Eng	-2.15
20	AS Eng	0.15
21	SW1T	4.86
22	NLG Lat	2.77
23	AW2B	1.07
24	NLG FA	-0.81
25	AFA	3.29
26	AW3B	12.57
27	SW3B	-1.78
28	MLG SFA	8.14
29	MLG AGA	2.23
30	SW2T	0.05
31	AW2T	8.29

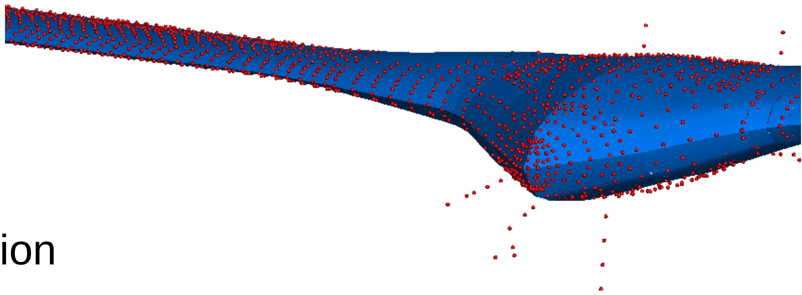


Flex Wing Empty Fuel		
Mode #	Description	Freq % Diff
	Significant	Δ < 3%
	Moderate	3% < Δ < 5%
	Least	5% < Δ
7	SW1B	-1.32
8	AW1B	0.46
9	SW1T	2.17
10	BRS Lat	0.83
11	SFA	0.24
12	AW1T	5.83
13	AMLG	0.23
14	SW2B	0.04
15	SMLG	2.59
16	Boom Lat	1.15
17	AWL	1.43
18	Boom Ver	0.98
19	AW2B	-0.36
20	SWL	1.30
21	Eng Sym	-2.88
22	Eng A/S	-2.00
23	NLG Lat	-0.20
24	AFA	5.26
25	NLGFA	0.41
26	SW3B	-0.64
27	MLG AFA	6.17
28	AW3B	8.41
29	MLG SFA	6.78
30	SW2T	3.63
31	AW2T	-2.76

Structural (Unsteady) Aerodynamics



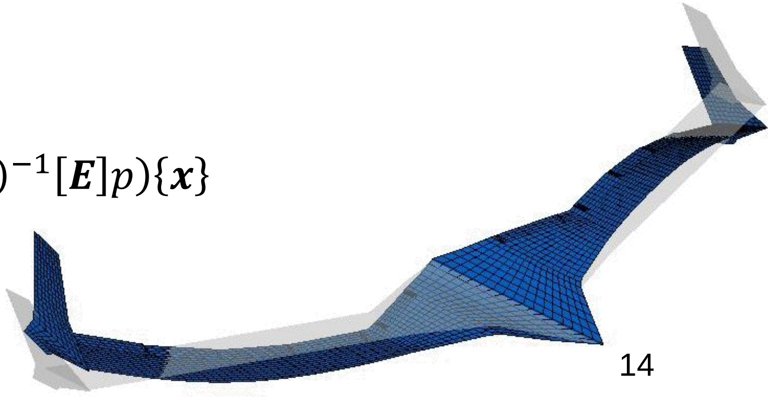
- ZAERO
  - Frequency Domain Panel Method
    - Potential flow based
    - Linear varying vortex (constant pressure) panels
      - Avoids singularities of Doublet Lattice
    - Assuming constant velocity at a fixed Mach
    - Forces in inertial modal reference frame
      - Must be transformed to stability frame
    - Provides frequency response at discrete reduced frequencies ($k = \bar{c}\omega / 2V_\infty$)
  - Infinite Plate Spline
    - Relates deflection of each panel to the motion of the structural grid points



- Roger's Rational Function Approximation
  - A transfer function is fit to the discrete points

$$\{\boldsymbol{Q}\} = -q_\infty([\boldsymbol{A}_0] + [\boldsymbol{A}_1]p + [\boldsymbol{A}_2]p^2 + [\boldsymbol{D}]([\boldsymbol{I}]p - [\boldsymbol{R}])^{-1}[\boldsymbol{E}]p)\{\boldsymbol{x}\}$$

  - Elements of $[\boldsymbol{A}_1]$ are updated by wind tunnel data
  - Used for B-52 flutter suppression (1975)



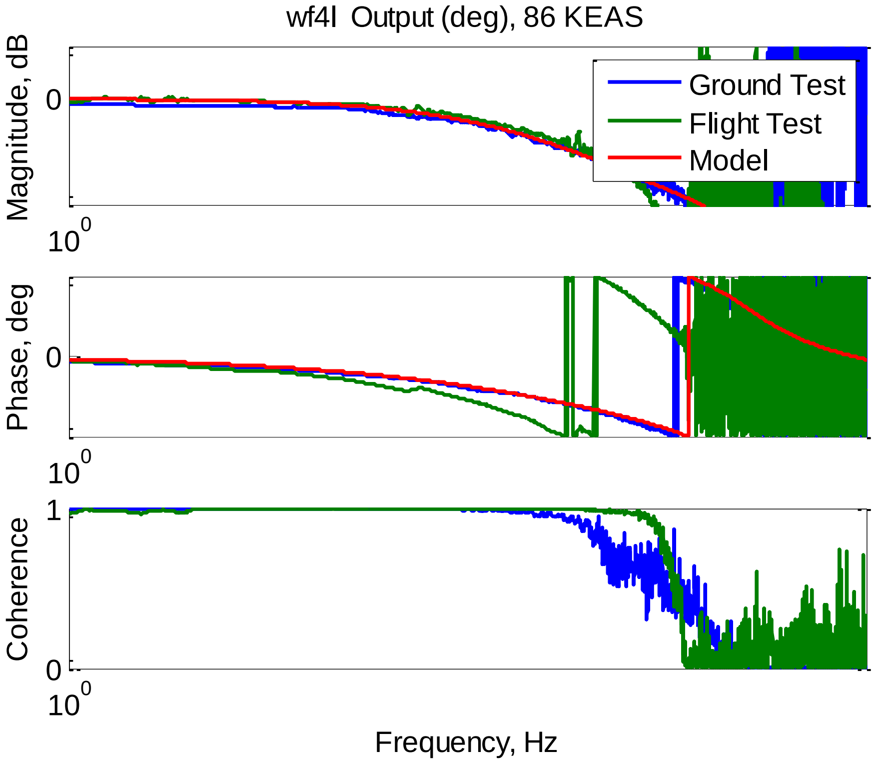
Sensor Models

- Coordinates of sensors match location on the vehicle
- Sensor Models from LM Simulation
  - – From sensor specifications
- Frequency of many sensors are below the structural frequencies

Output	Frequency, Hz	Damping	Noise RMS	
Vt	5	1	0.388769	knots
alpha	5	1	0.4	deg
q	55	0.7	0.03	deg/s
theta	5	1	0.4	deg
gamma	5	1	0.4	deg
beta	5	1	0.4	deg
p	55	0.7	0.03	deg/s
r	55	0.7	0.03	deg/s
phi	5	1	0.4	deg
psi	5	1	2	deg
x	1	1	6.56168	ft
y	1	1	6.56168	ft
h	1	1	9.84252	ft
Nx	20	1	0.000671	g
Ny	20	1	0.000671	g
Nz	20	1	0.000671	g
ASESNSR 100	100	0.6	0.025	g
ASESNSR 400	100	0.6	0.025	g
ASESNSR 600	100	0.6	0.025	g
ASESNSR 1000	100	0.6	0.025	g
ASESNSR 1100	100	0.6	0.025	g
ASESNSR 1300	100	0.6	0.025	g

Actuator Model

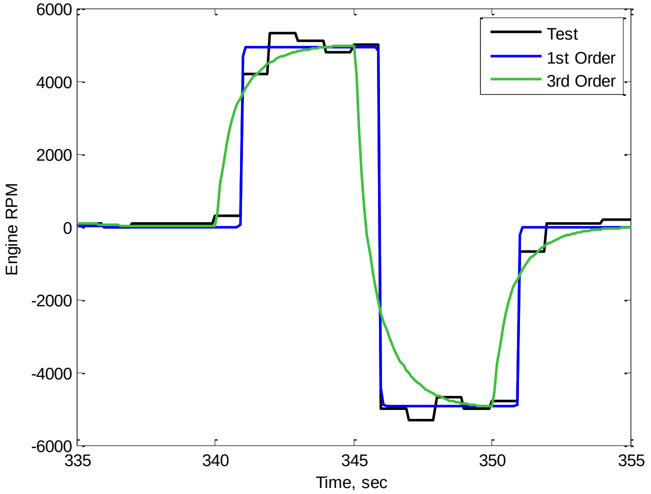
- Models identified from ground testing
  - Logarithmic frequency sweeps to actuators in the wing
  - 3rd order for NDoF
- Models validated by flight test
  - Phase errors due to telemetry
  - Some errors due to flexing of the surface
- Identified Models
  - Gain fixed, 1
  - Frequency domain identification

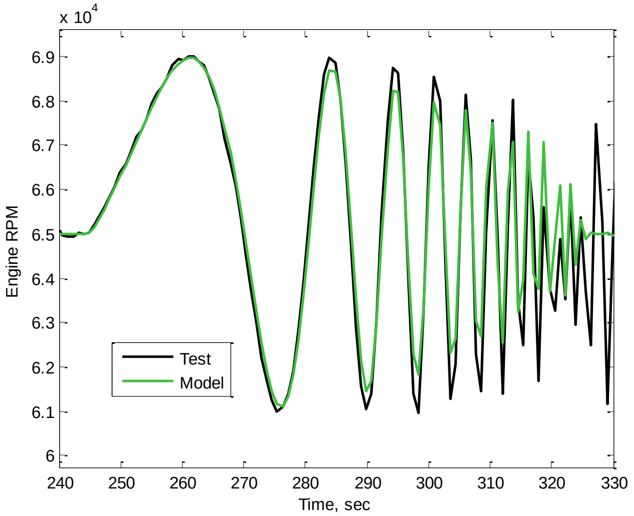


$$H(s) = \frac{d_0}{s^3 + d_2 s^2 + d_1 s + d_0}$$

Engine Models

- Identified Model
  - Using a doublet to identify model
  - Communication delay from 1st order model
    - Assume half of the delay is to send the message
  - Identify 2nd order model
  - Validation by frequency sweep
    - Aliasing at high frequencies



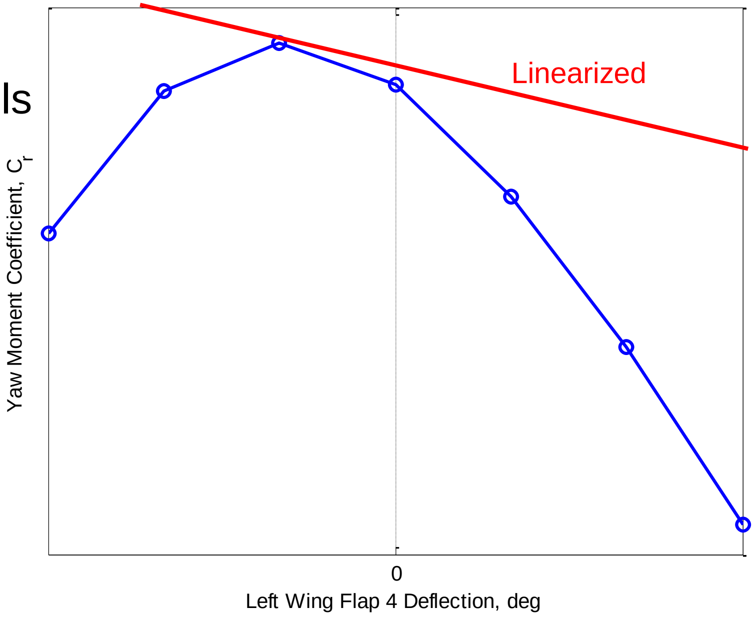


Modeling and Simulation

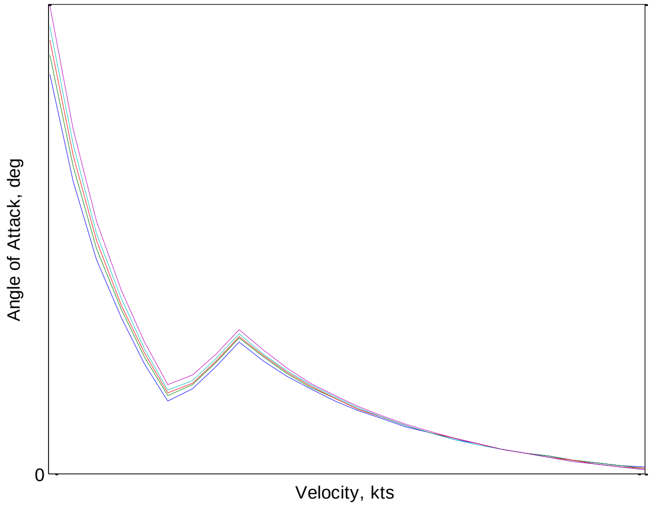
MODEL ANALYSIS RESULTS

Caveats

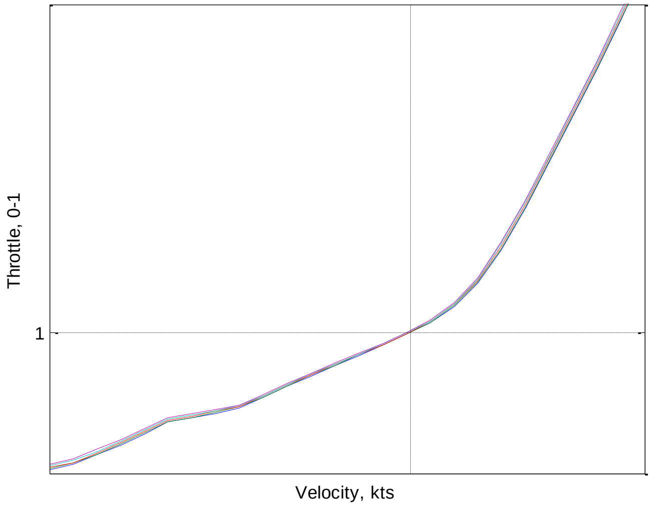
- Linear 36DoF Models
  - – Yaw control is due to nonlinearities
    - Cannot asses yaw control with linear models
  - – Simulation is not real-time
- Body Flap effects are uncertain
  - – May be effected by landing gear wake
  - – Usage is limited to mitigate risks
- Pitching moment due to throttle
  - – Nonlinear simulation over predicts
  - – Linear models are predicting much better

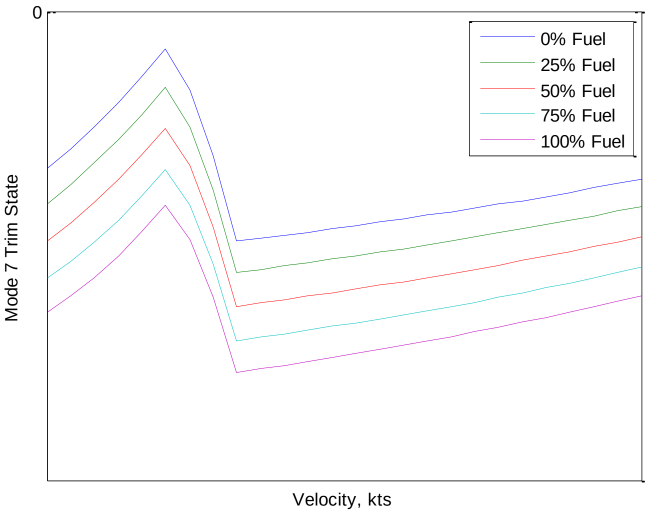


Stiff Wing Trim Verification (Fido)

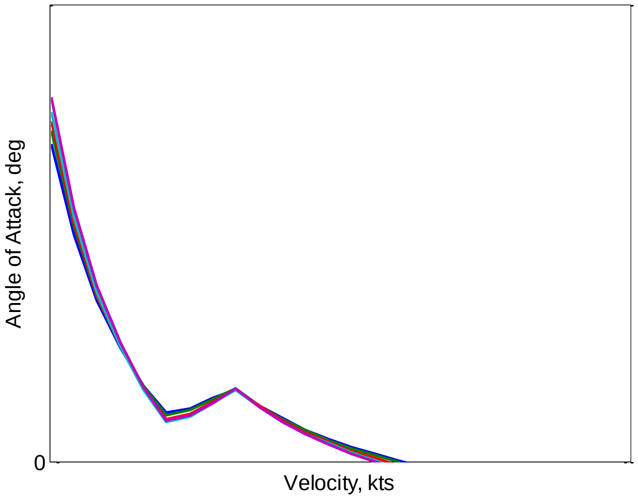


- Trim results are similar to those seen in nonlinear simulation

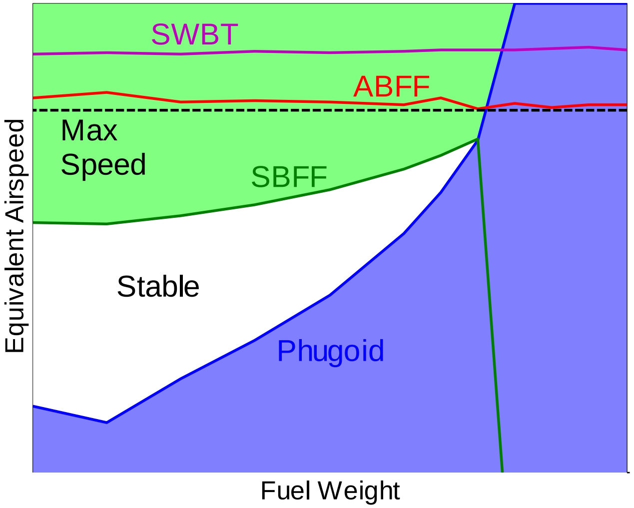


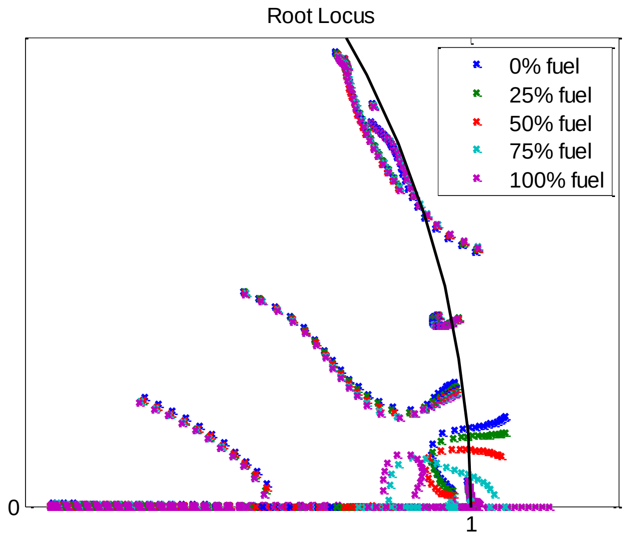


Flex Wing Verification (Fido)



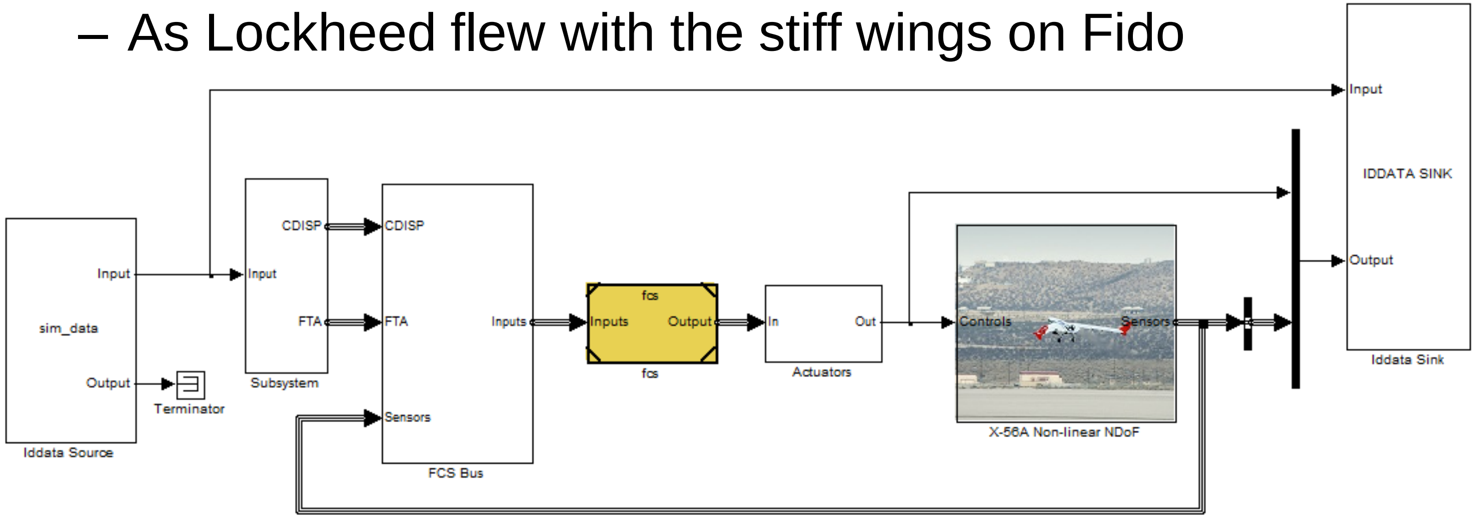
- Flex wing has a small region of stability
  - Only one flutter mode in the flight envelope
  - Body freedom flutter very dependent on fuel weight
- Statically unstable at high fuel weights
  - Unstable Phugoid



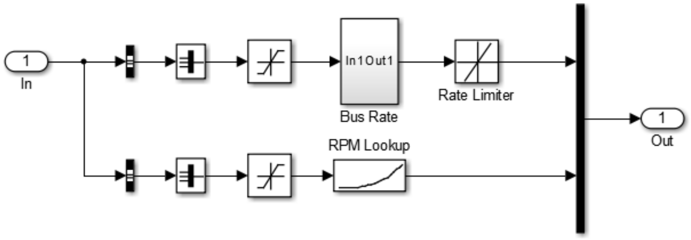


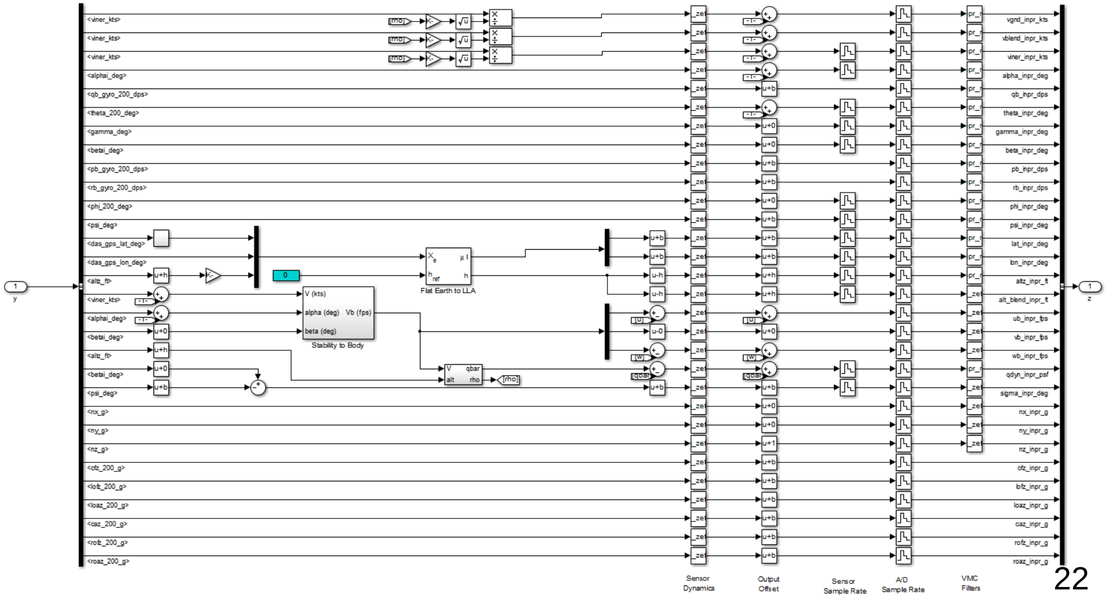
NDoF Validation Simulation

- Simulation with MAD OFP
  - As Lockheed flew with the stiff wings on Fido

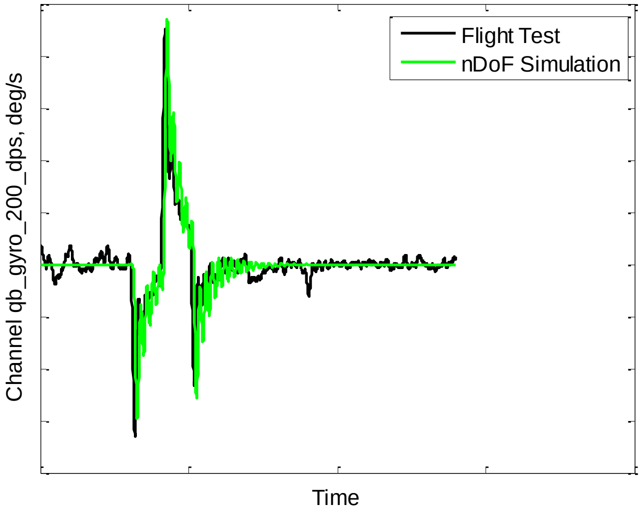


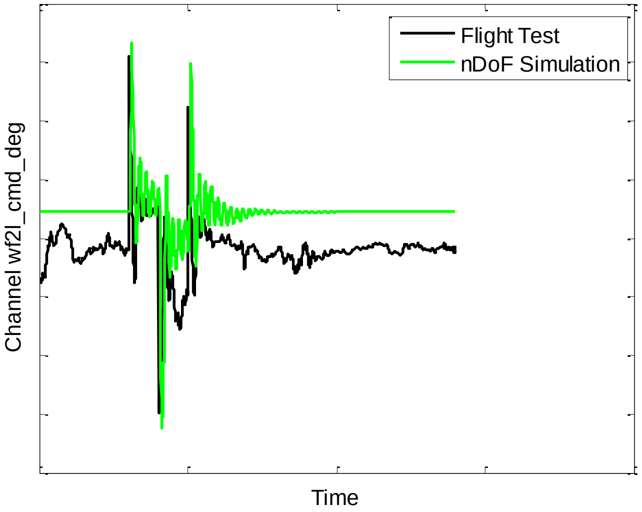
- Discrete time
- Sensor dynamics
- Signal Processing Filters
- Actuator nonlinearities

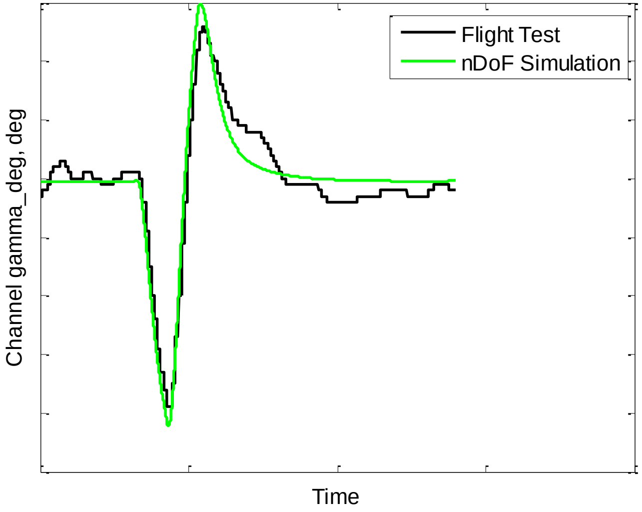


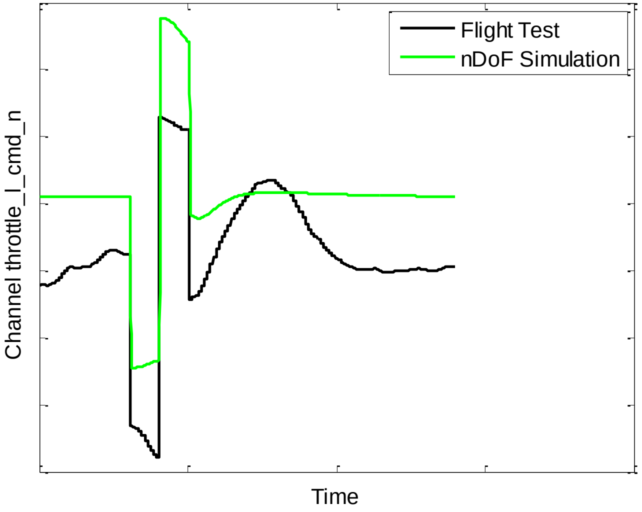


Gamma Doublet (70 KEAS, 46% fuel)

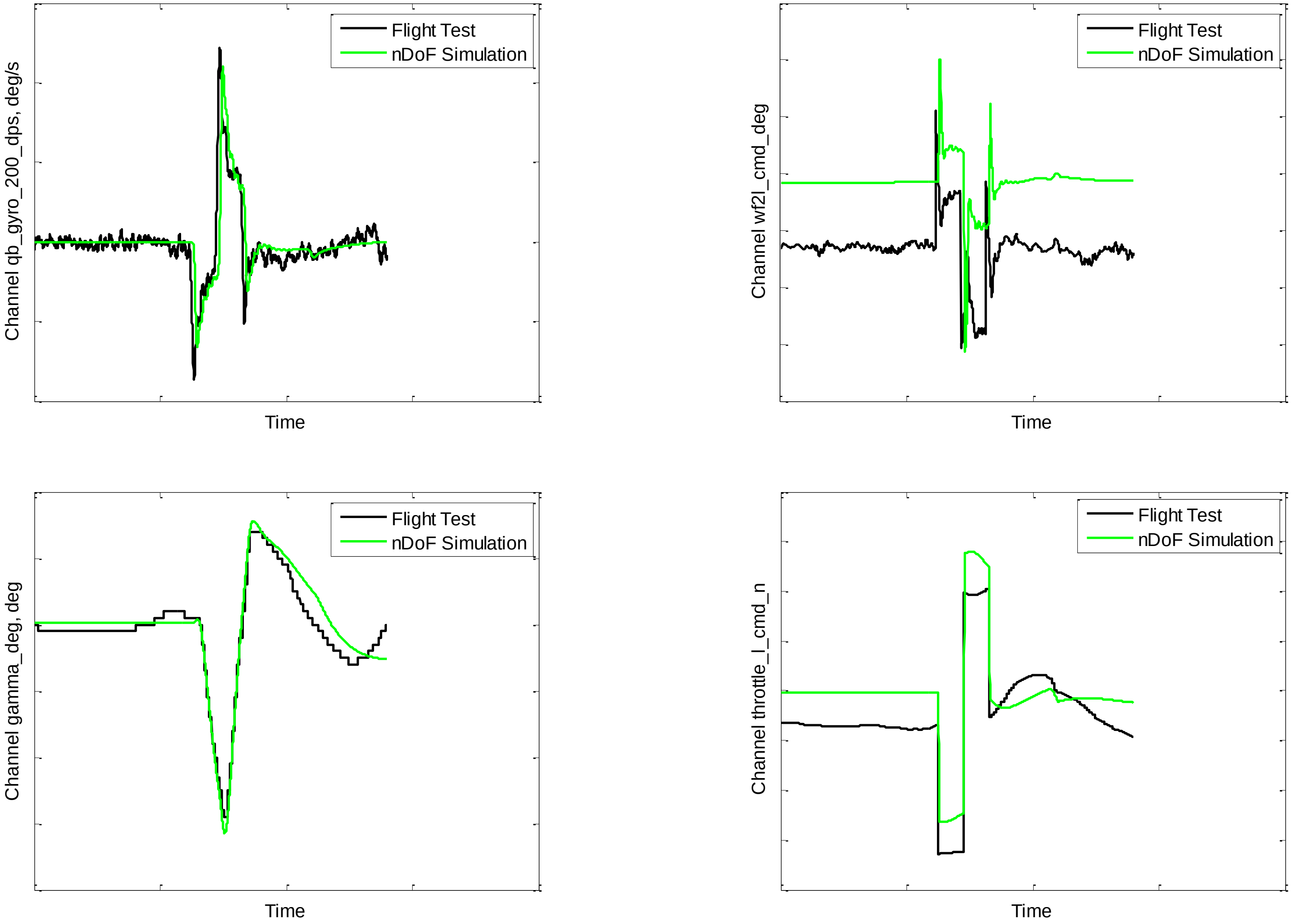




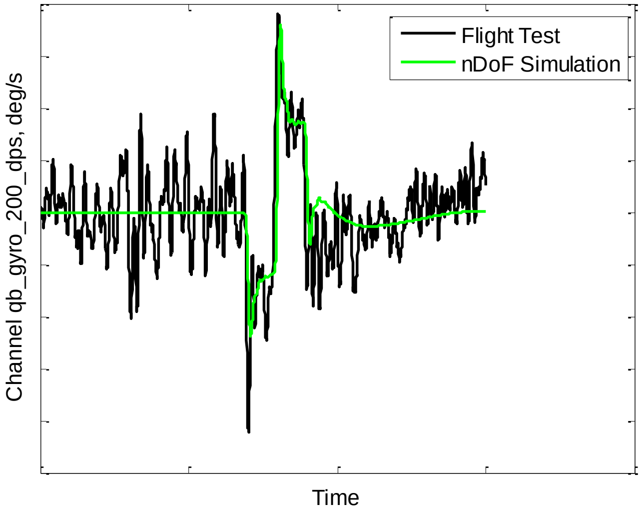


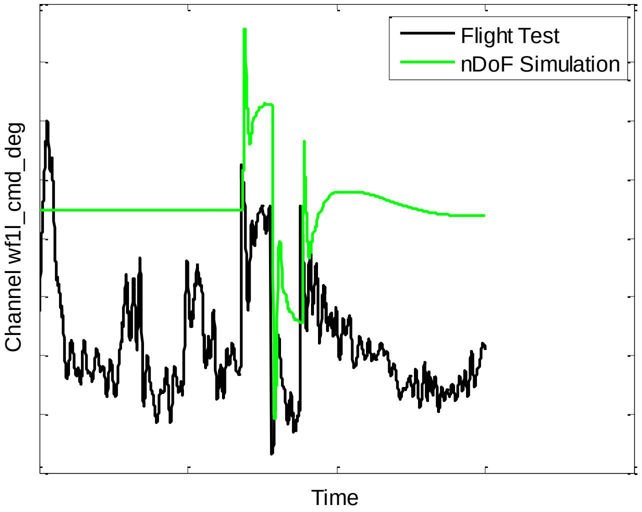


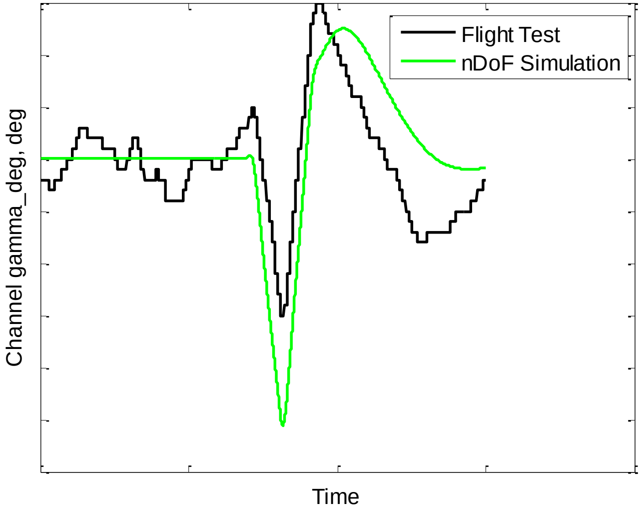
Gamma Doublet (86 KEAS, 58% fuel)

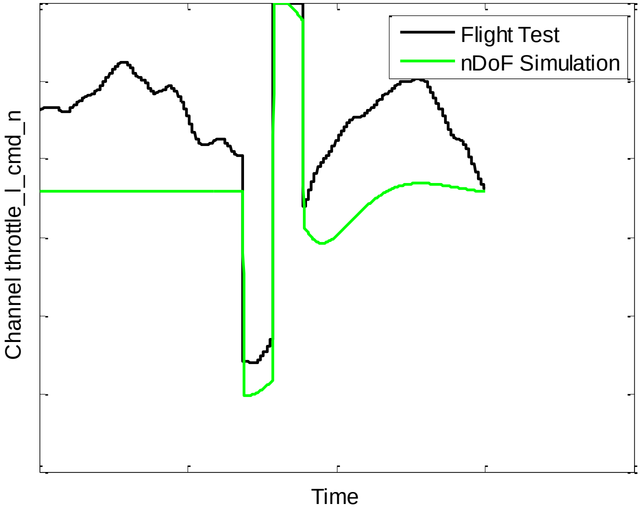


Gamma Doublet (108 KEAS, 31% fuel)

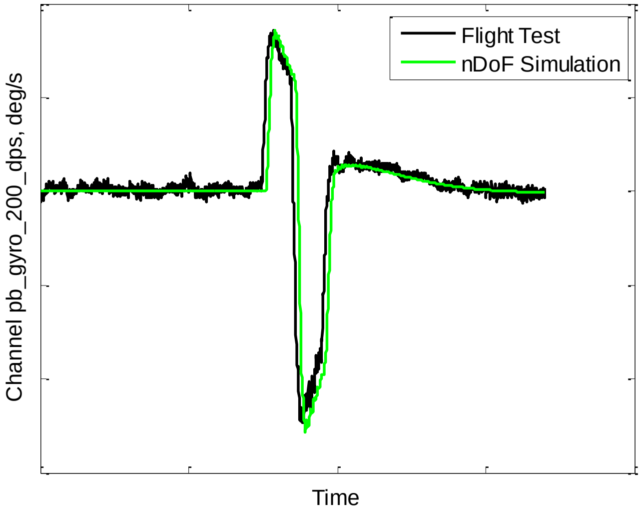


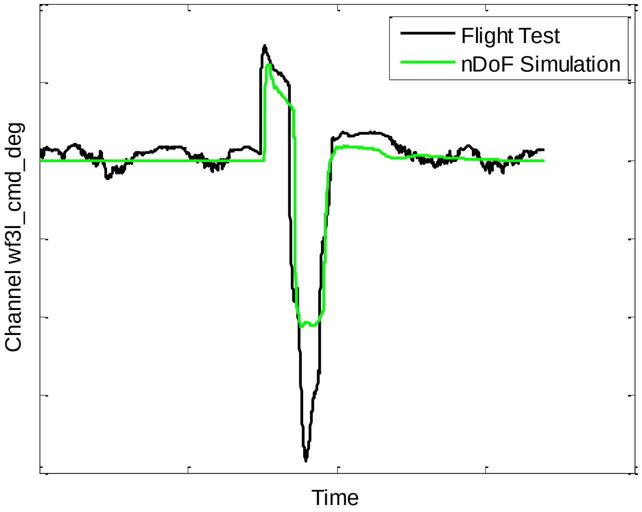


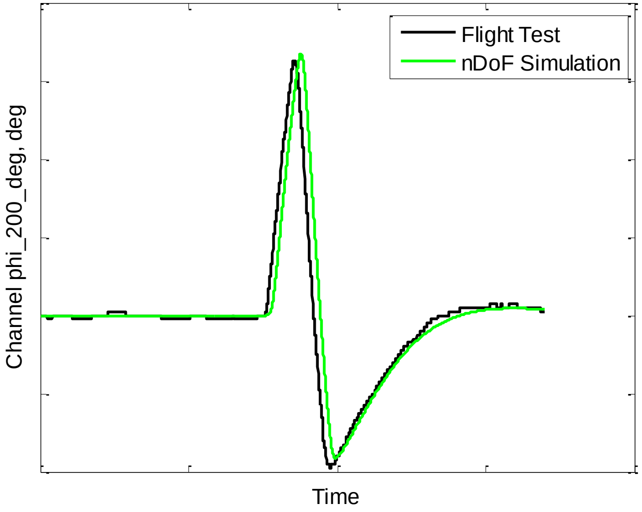


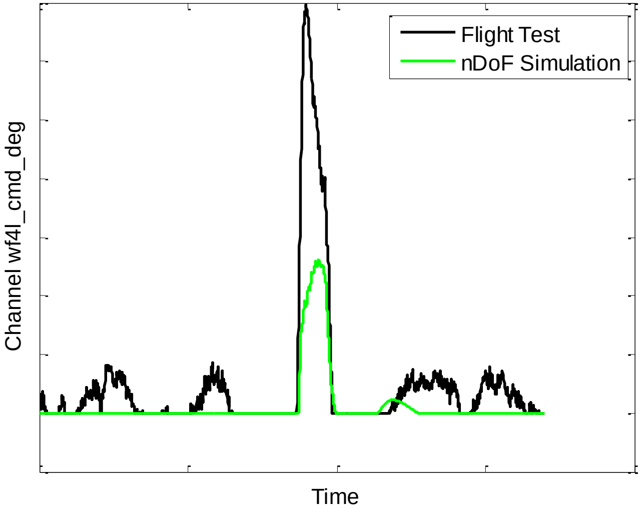


Roll Doublet (86 KEAS, 58% fuel)

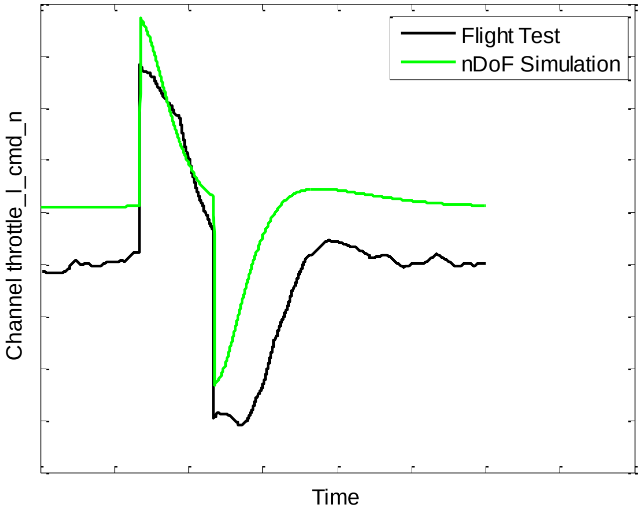


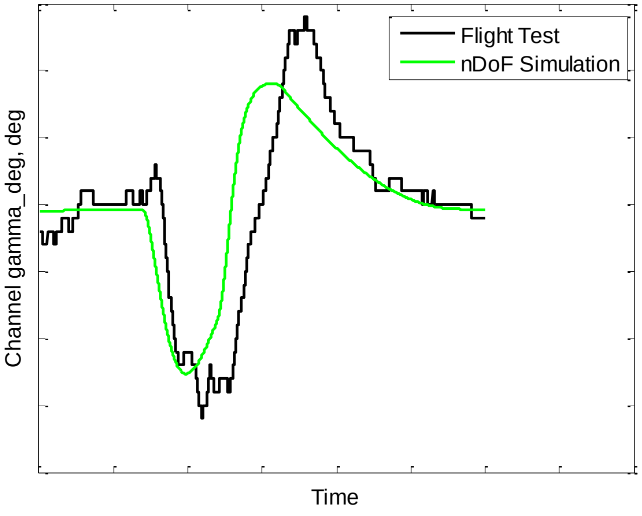


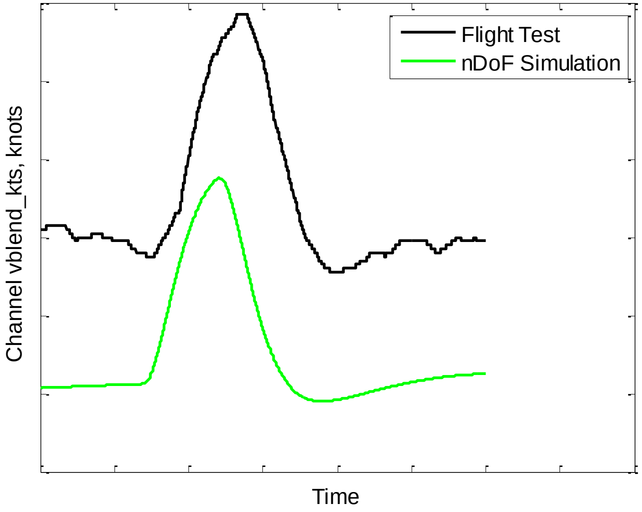


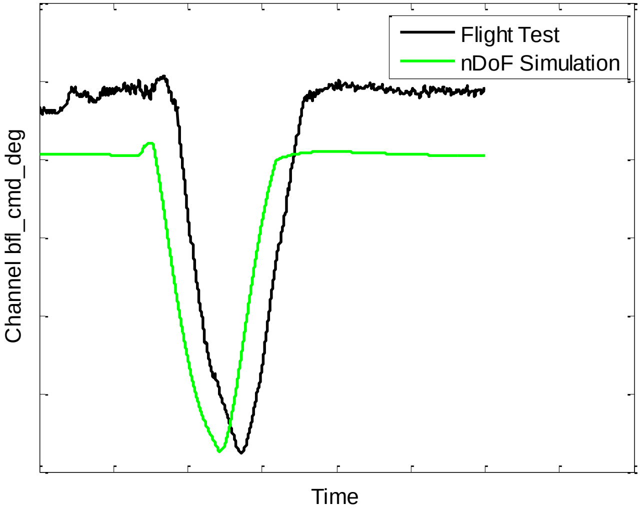


Velocity Singlet (70 KEAS, 44% fuel)

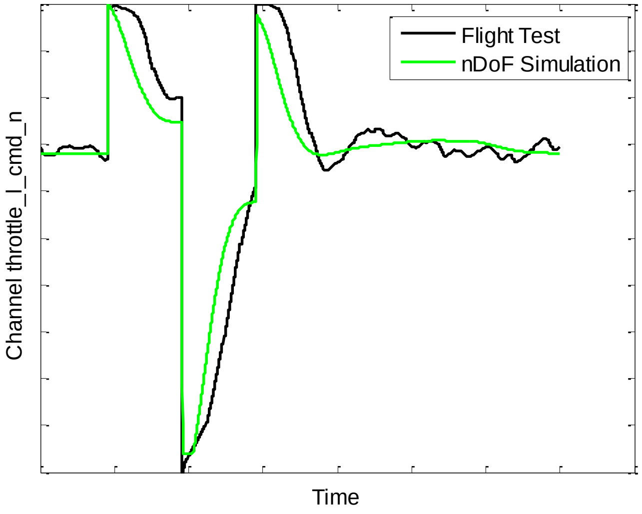


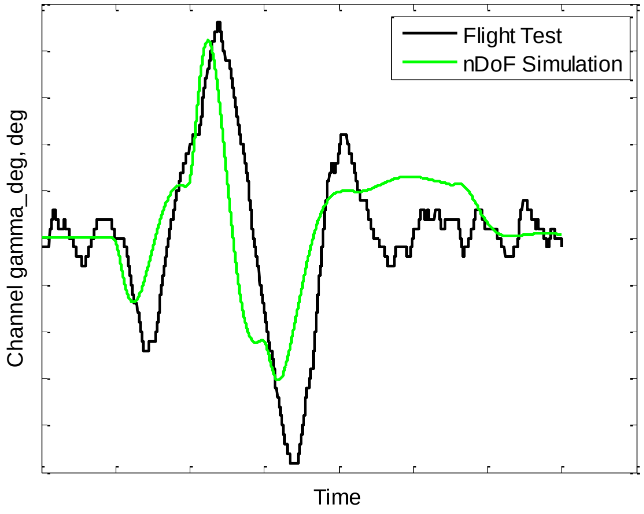


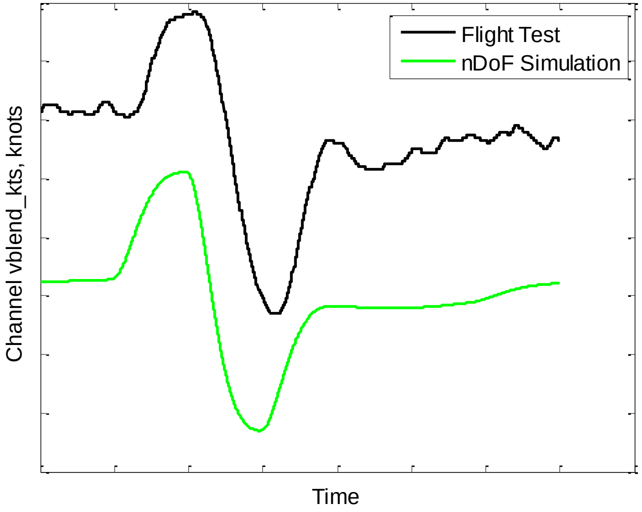


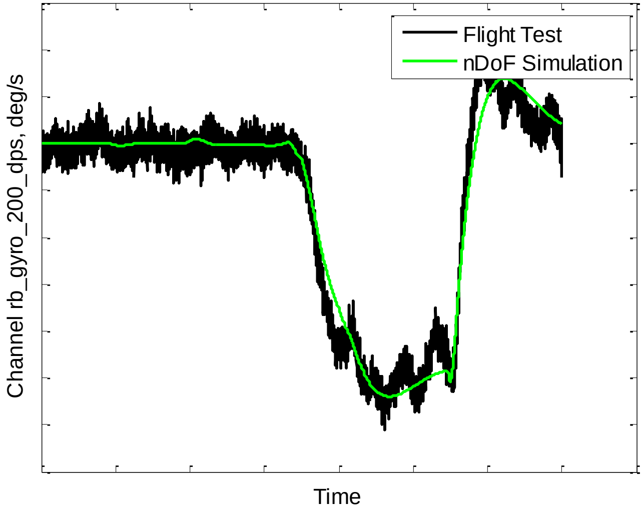


Velocity Doublet (100 KEAS, 53% fuel)

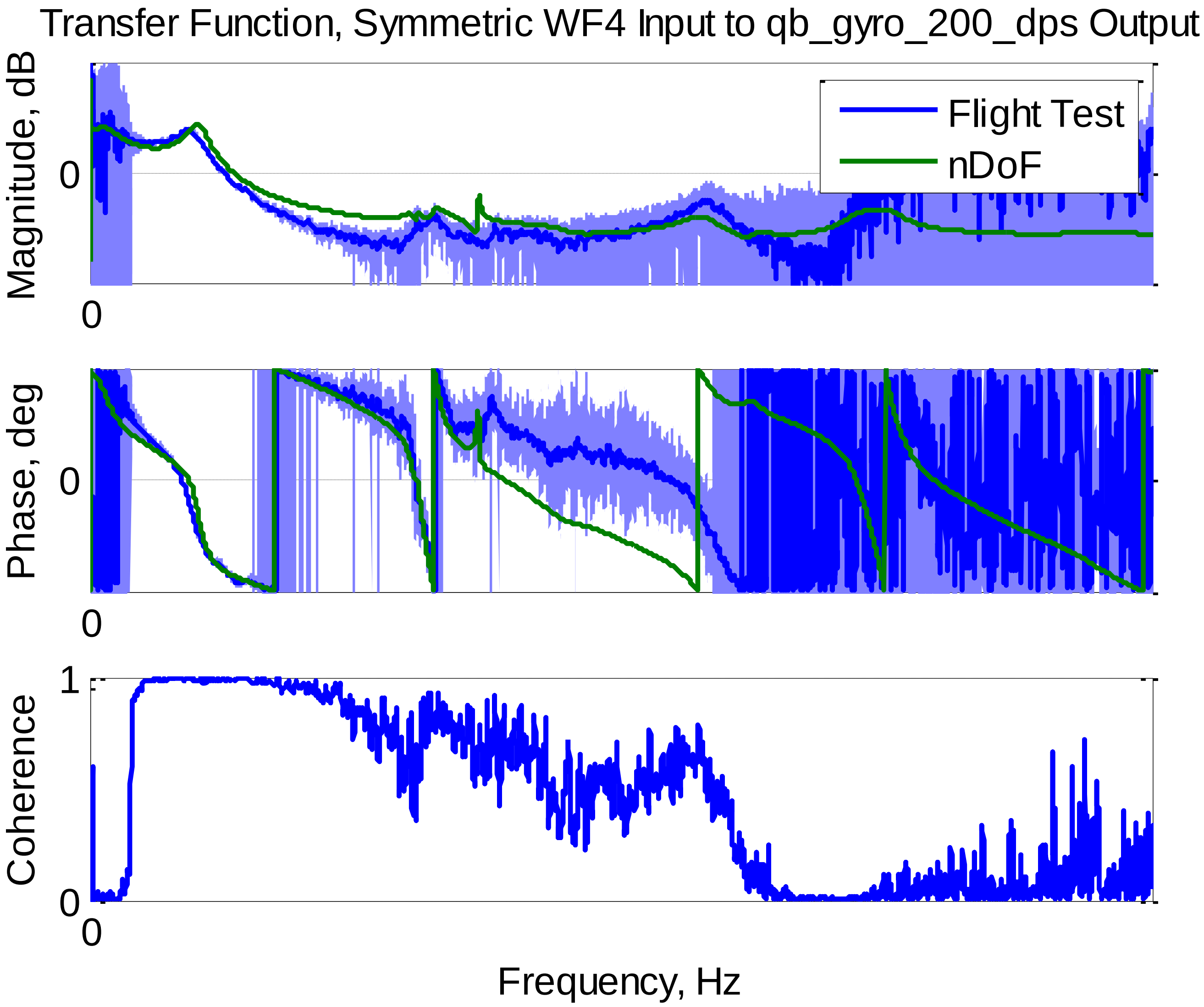




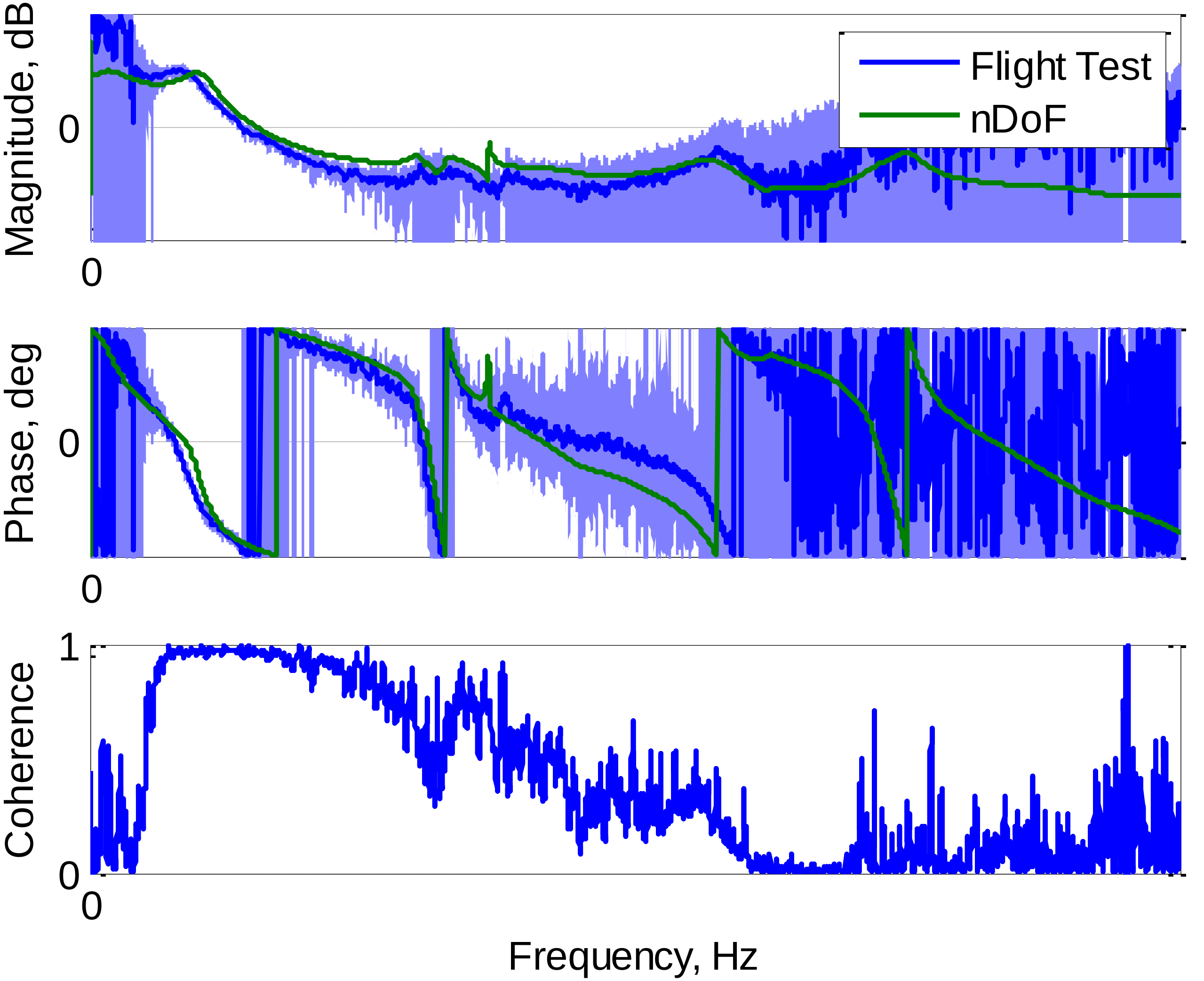




Symmetric Frequency Sweep (86 KEAS)

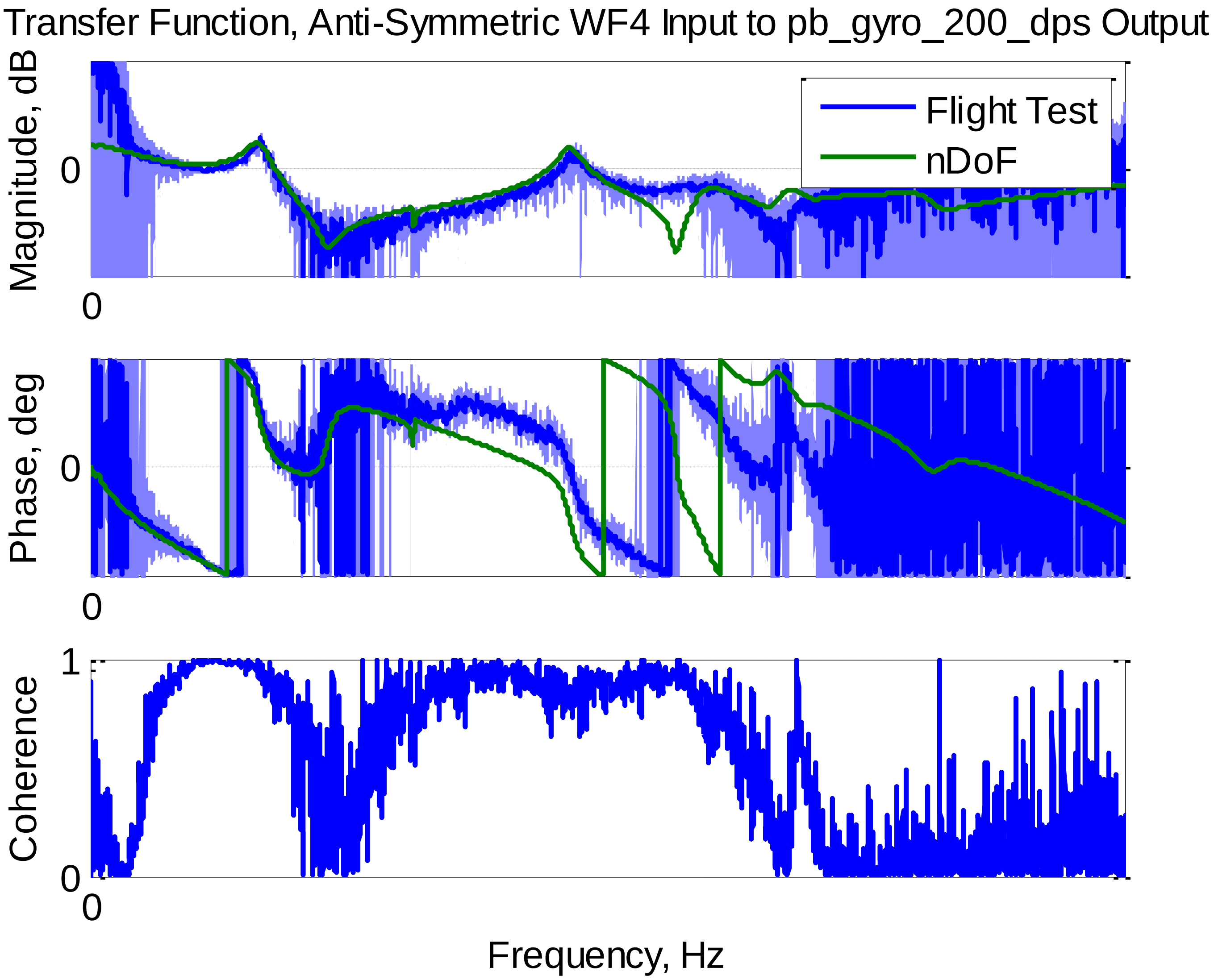


Symmetric Frequency Sweep (124 KEAS)



Transfer Function, Symmetric WF4 Input to qb_gyro_200_dps Output

Anti-symmetric Frequency Sweep (107 KEAS)



Conclusions

- Stiff wing models have been validated from Lockheed Martin flight test data
  - Validation limited to low mass and low speed
  - Stiff Wing FEM has low torsional stiffness
- Flex wing models have been verified
  - Only difference is the FEM
  - Similar to results from Lockheed
  - Do not have flight test data yet
- Working on Piloted Real-Time simulation
  - Adding structural degrees of freedom
    - Requires consistent state definitions
    - Fewer DoF required
  - Structural effects into sensor models
  - Stable numerical integration

Questions?