National Aeronautics and Space Administration
Dryden Flight Research Center

SOFIA Stratospheric Observatory for Infrared Astronomy

SOFIA 747-SP
Structural Dynamics Overview

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NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED06-0233-1 Date: February 2, 2006 Photo By: L-3 Communications/USRA

The German-built 100-inch telescope that is the heart of NASA's Stratospheric Observatory for Infrared Astronomy is nestled in the SOFIA 747's rear fuselage.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED07-0079-22 Date: April 26, 2007 Photo By: Carla Thomas

NASA's SOFIA 747SP shows evidence of modification to its aft fuselage contours to accommodate a 16-foot-tall cavity door for its 45,000-pound infrared telescope

Certification Requirements

- FAR Part 25.629 requires demonstration that the aircraft has flutter margins of at least 20% in equivalent airspeed beyond the structural design (V_D/M_D) envelope
- The scope of the SOFIA structural modifications require that flutter margins be demonstrated using a combination of
  - Analysis
  - Ground Vibration Testing
  - Flight Flutter Testing

Analysis Process

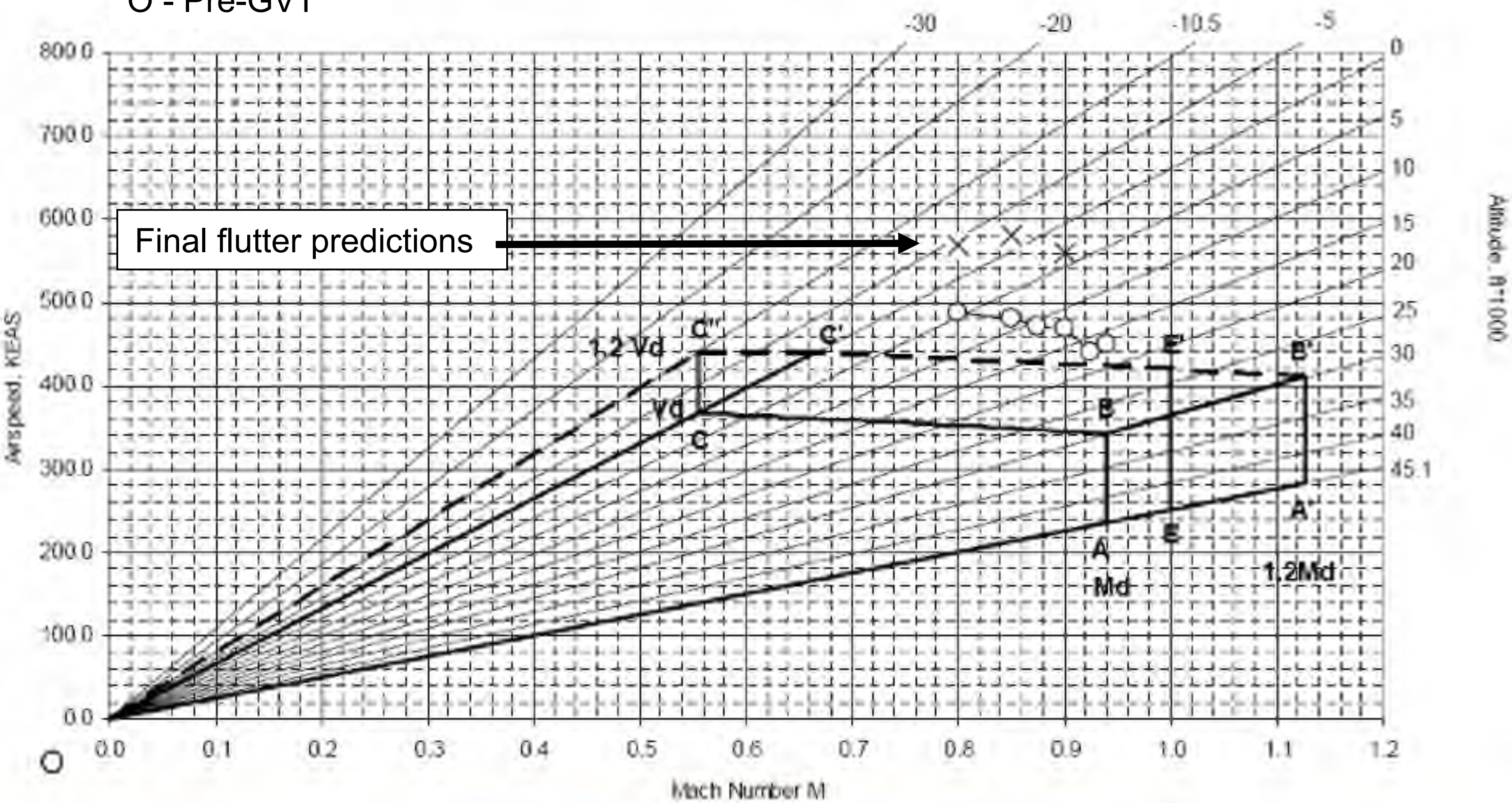
- Baseline 747SP flutter model
  - Derived from -100,-200 model
  - Validated by SOFIA Baseline testing
- SOFIA flutter model
  - SOFIA mass distribution changes per program Weight & Balance Reports
  - SOFIA fuselage stiffness changes per Certification Finite Element Model
  - Telescope Assembly & Simulator
    - Simulator has no isolation system
    - TA isolation system has different configurations
  - Validation through post-modification testing
    - Aircraft System and Observatory GVT and flight testing

Analysis Results

- SOFIA vs. Baseline 747SP flutter margins
  - Critical flutter mechanism unchanged
    - Antisymmetric wing / outboard engine / fuselage
  - SOFIA aft fuselage stiffer than Baseline
    - Parametric studies show that increased fuselage stiffness has a negligible effect on flutter speeds
  - Some interaction of telescope and aircraft modes
    - No new flutter mechanisms predicted
    - No dramatic changes in speeds of existing mechanisms
  - Wing fuel distribution remains dominant parameter
  - Flutter margins for all mechanisms predicted to be greater than the required 20%

Closed Door Predicted Flutter Margin

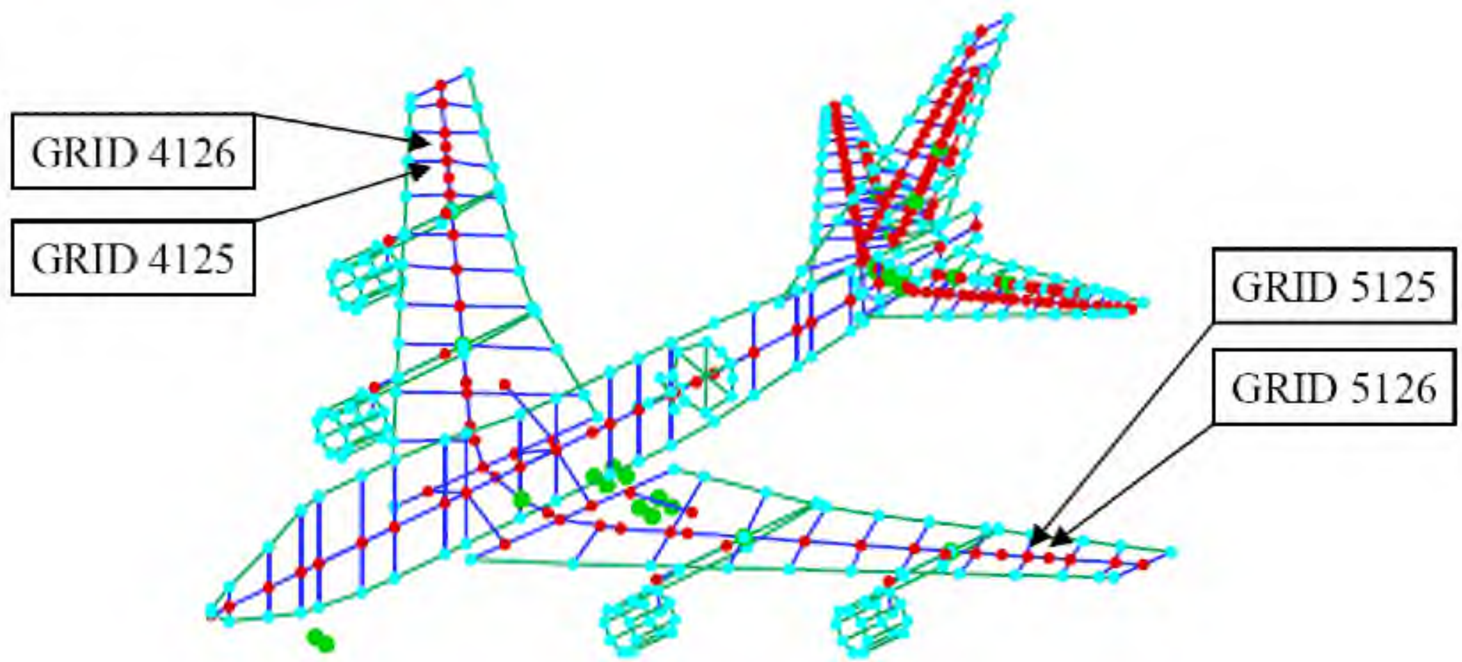
X - Post-GVT
O - Pre-GVT



Note: Full outboard wing reserve tanks 2 & 3 full, TA caged and braked, S1ffff fuel condition

ZAERO Flutter compared to NASTRAN

- Wingtip Res2&3 fuel load sensitivity



ZAERO Flutter compared to NASTRAN

- Wingtip Res2&3 fuel load sensitivity

Table 4. Summary of flutter analysis results with symmetric fuel variation.

	Flutter Speed (knots)	Flutter Frequency (Hz)	Flutter Dynamic Pressure (psf)	Flutter Altitude (ft)
Full Fuel	562.7	1.9971	1080.0	-241.0
75% Fuel	574.3	1.9928	1340.0	-6290.0
50% Fuel	581.6	1.9882	1527.0	-10100.0
25% Fuel	585.9	1.9844	1655.0	-12400.0
Empty Fuel	587.1	2.0357	1691.0	-13100.0

- Assumed structural damping = 2 %
- Fuel mass @ 4126,4125,5126,5125 - varying symmetrically

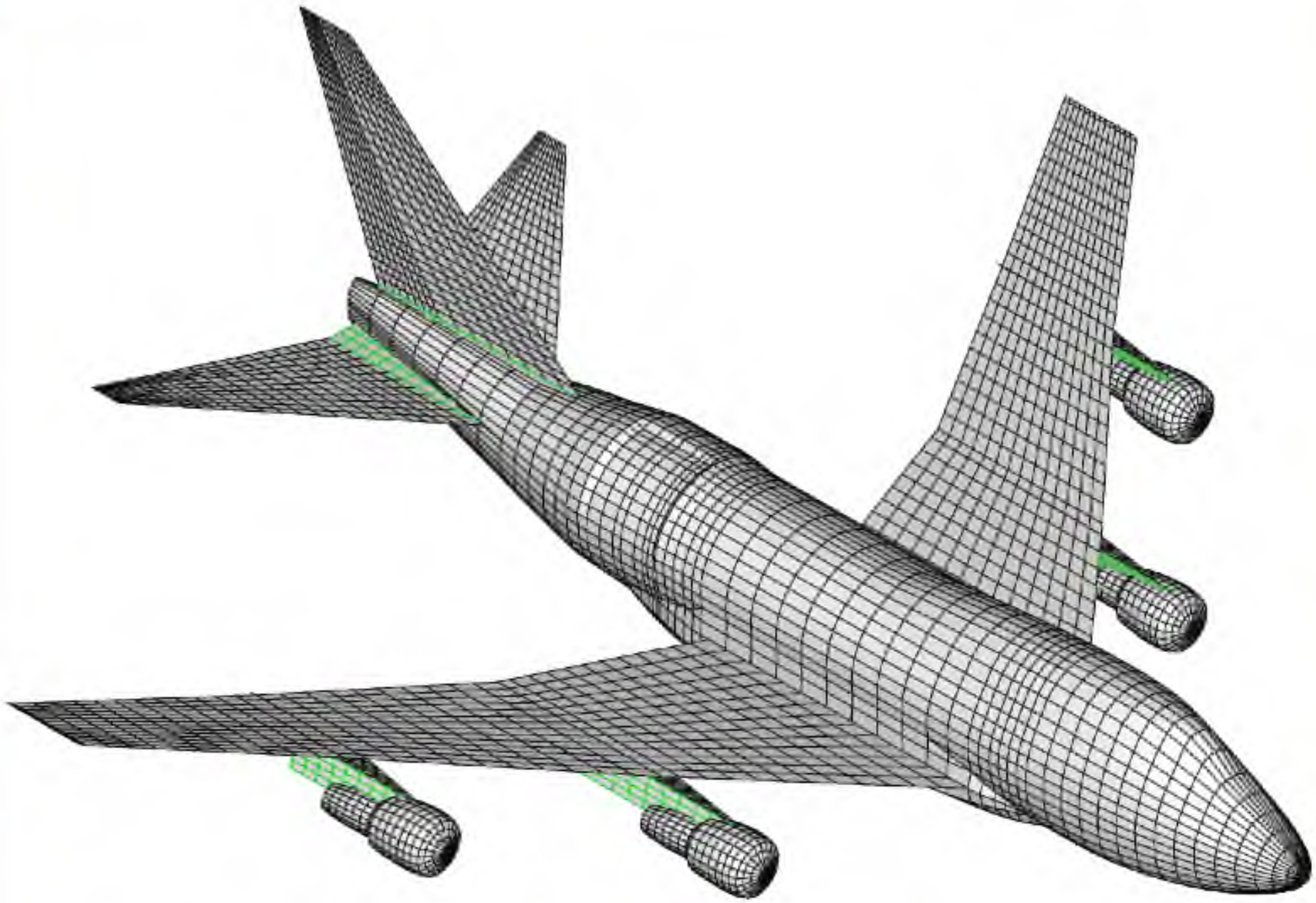
Table 5. Summary of flutter analysis results with asymmetric fuel variation.

	Flutter Speed (knots)	Flutter Frequency (Hz)	Flutter Dynamic Pressure (psf)	Flutter Altitude (ft)
Full Fuel	562.7	1.9971	1080.0	-241.0
88.7% Fuel	565.5	1.9963	1140.0	-1690.0
77.4% Fuel	568.0	1.9955	1195.0	-3000.0
66.1% Fuel	570.2	1.9947	1243.0	-4160.0
54.8% Fuel	572.1	1.9939	1284.0	-5130.0

- Assumed structural damping = 2 %
- Fuel Mass @ 4126,4125 - maintaining full fuel
- Fuel Mass @ 5126,5125 - varying

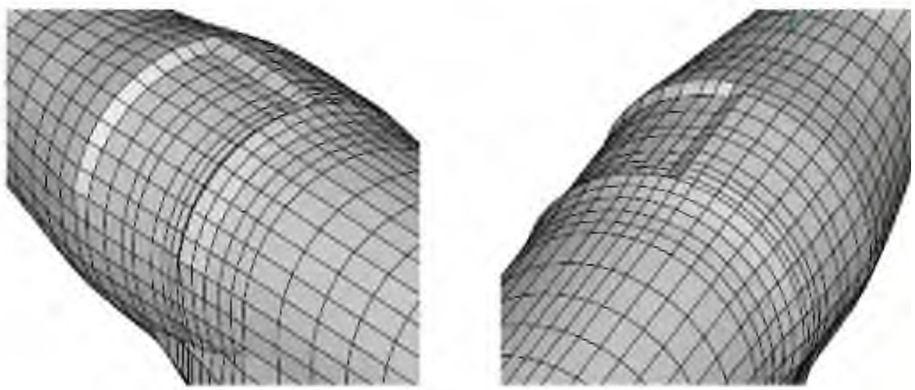
Zaero Sensitivity of Aero Modeling

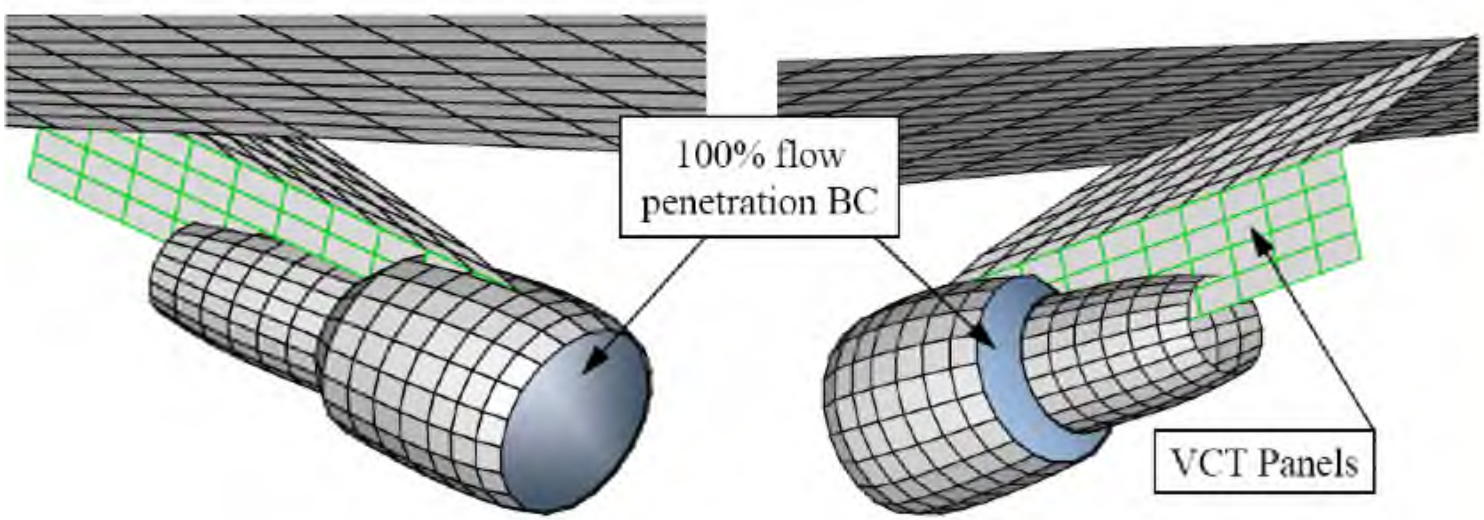
- Increased Aerodynamic Model Fidelity



Zaero Sensitivity of Aero Modeling

- Increased Aerodynamic Model Fidelity





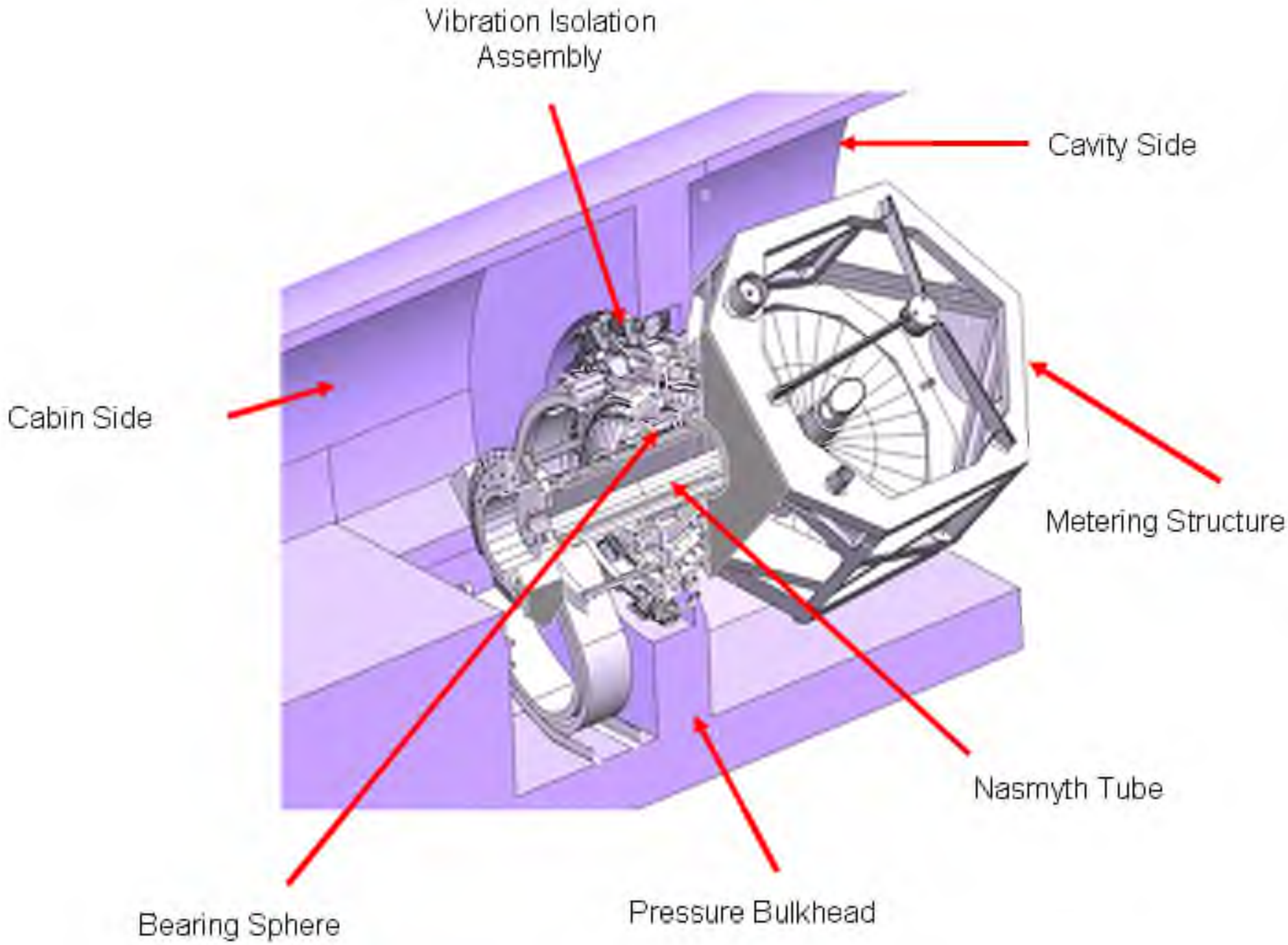
Zaero Sensitivity of Aero Modeling

- Increased Aerodynamic Model Fidelity of Engines was very important

Table 3. Flutter analysis results summary for the various aerodynamic models.

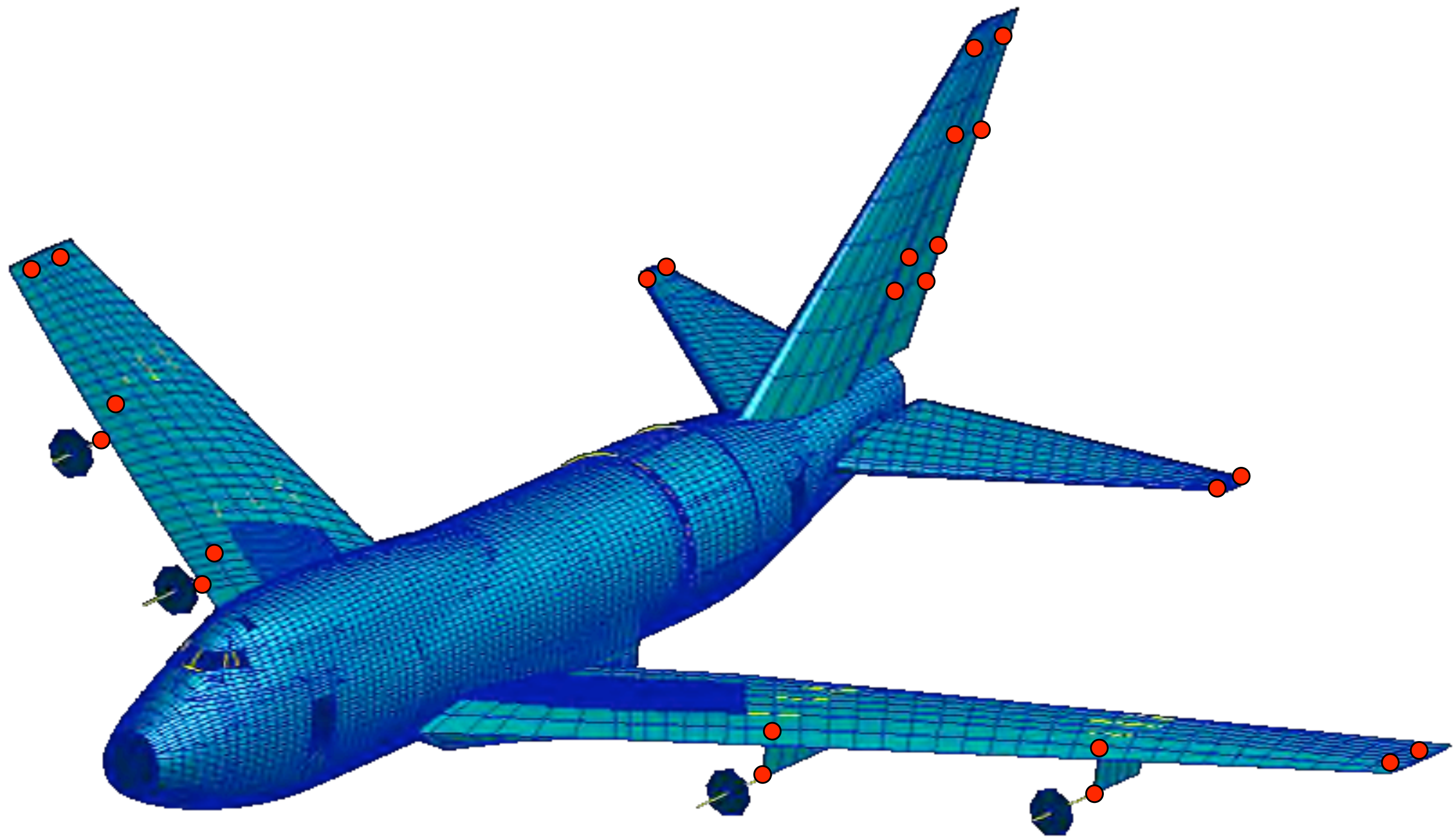
	Flutter Speed (knots)	Flutter Frequency (Hz)	Flutter Dynamic Pressure (psf)	Flutter Altitude (ft)	Flutter Mode
NASTRAN[1]	565.0	1.8135	1137.4	-	-
MODEL-A[2]	564.1	1.8376	1111.0	-987.0	14
MODEL-B[3]	564.7	1.8345	1124.0	-1300.0	14
MODEL-C[4]	562.7	1.9971	1080.0	-241.0	12

1. Provided by NASA Dryden
2. Simple fuselage and engine nacelle Model (Figure 2.1)
3. Detailed fuselage and simple engine nacelle Model (Figure 2.4)
4. Detailed fuselage and engine nacelle Model (Figure 2.7)

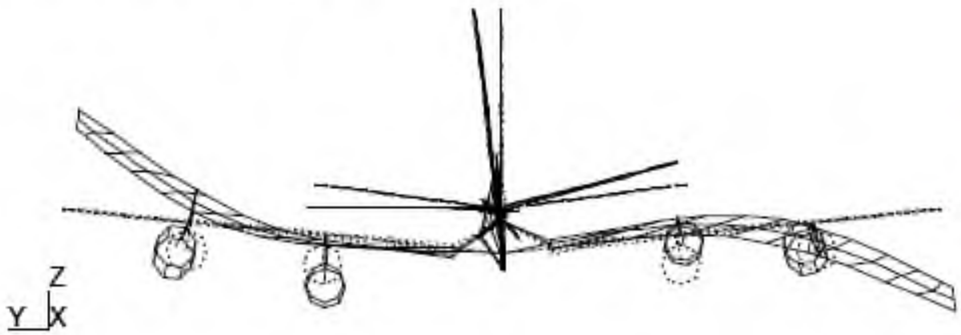

Vibration Isolation Assembly
Cavity Side
Cabin Side
Metering Structure
Nasmyth Tube
Bearing Sphere
Pressure Bulkhead

Aircraft Accelerometer Locations

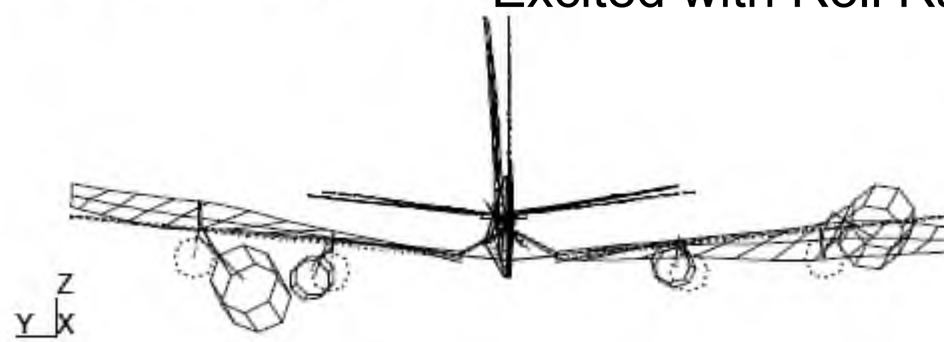
- Segment 1 – Closed Door aircraft handling envelope expansion



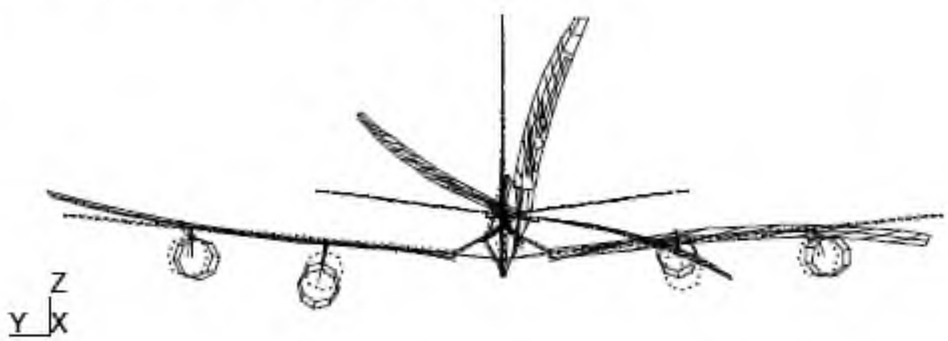
Wing 1st Bending Anti-Sym
- Excited with Yaw Rap



Wing 1st Torsion Anti-Sym
- Excited with Roll Rap

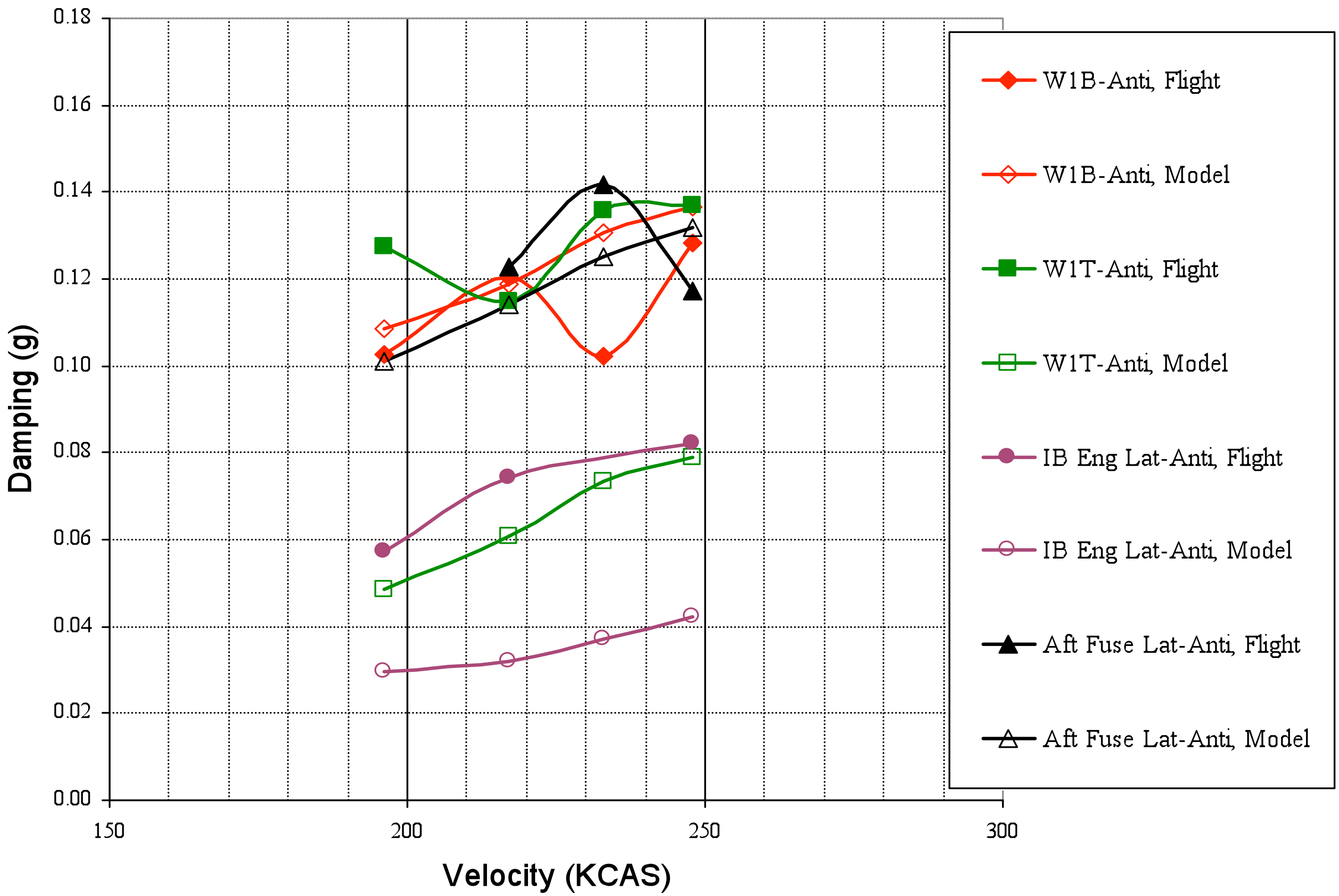


Aft Fuselage Torsion/Bending
- Excited with Yaw Rap



Segment-0 Flight Test Results

- Flutter Raps vs. Analytical Prediction –
  - Damping Value Method; Sub-critical Advantage
  - 15,000 ft



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IADS Flight Test Displays

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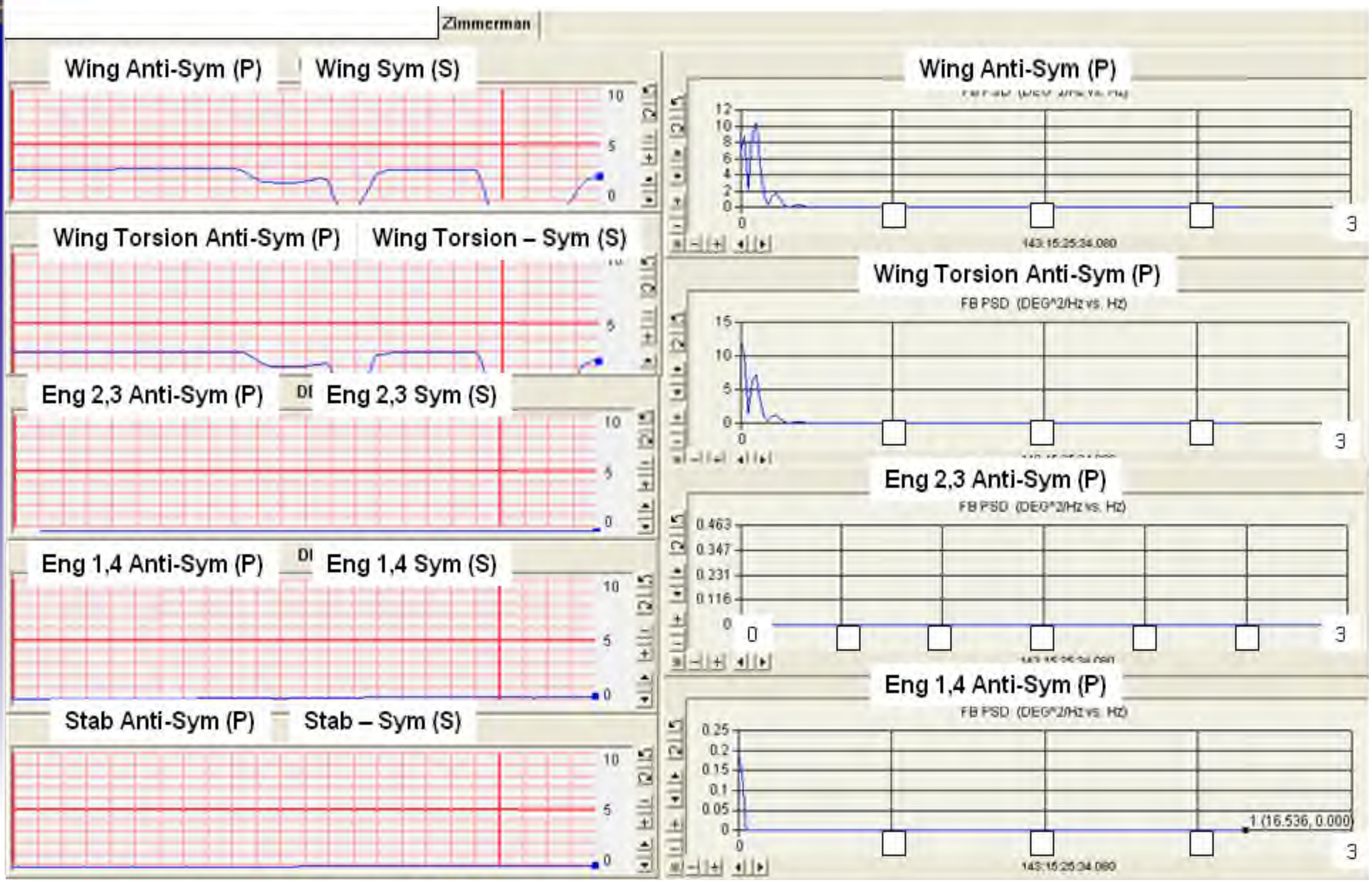
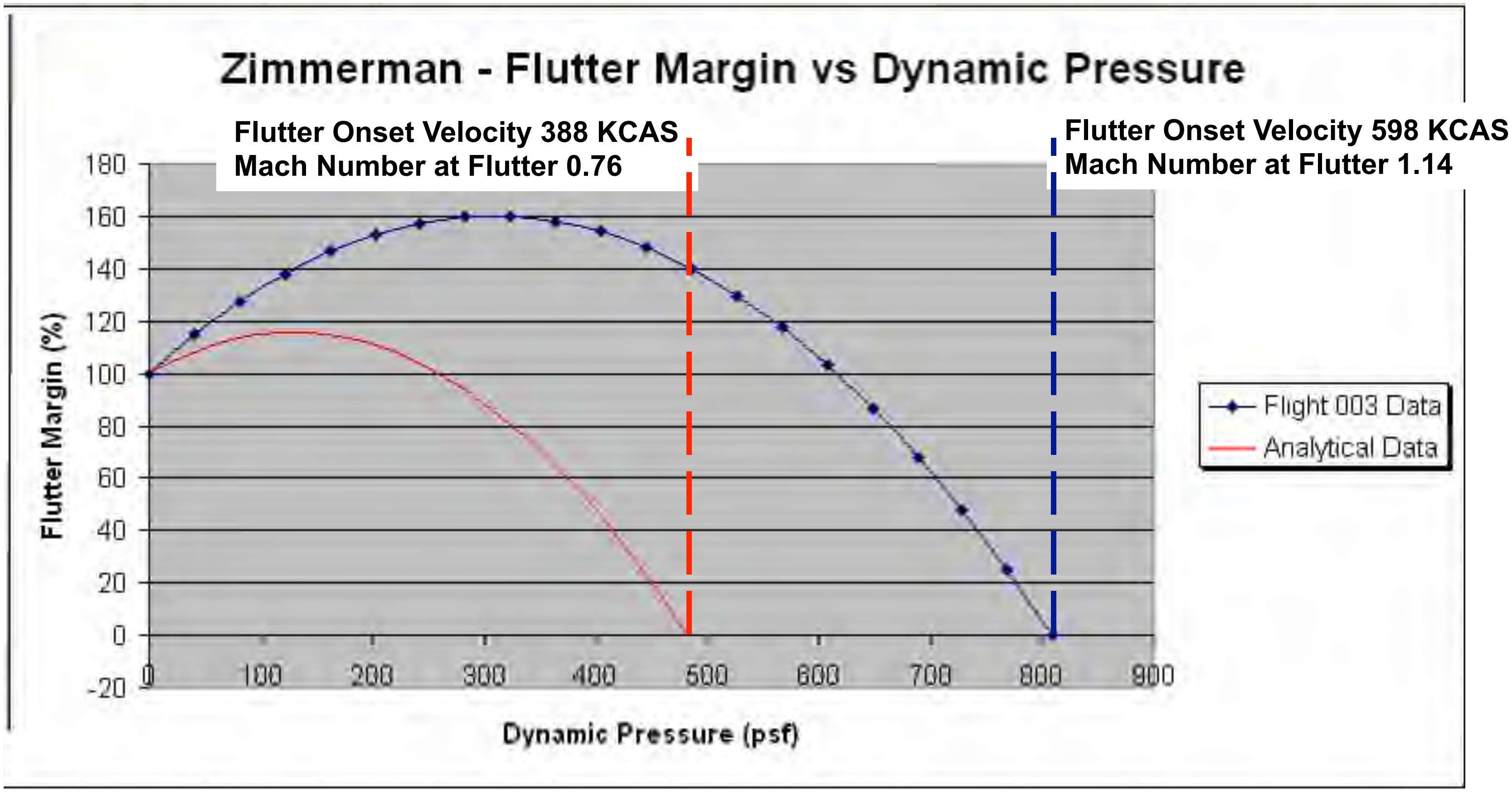
Tab6 - Zimmerman Input Data (Parameter Identification)



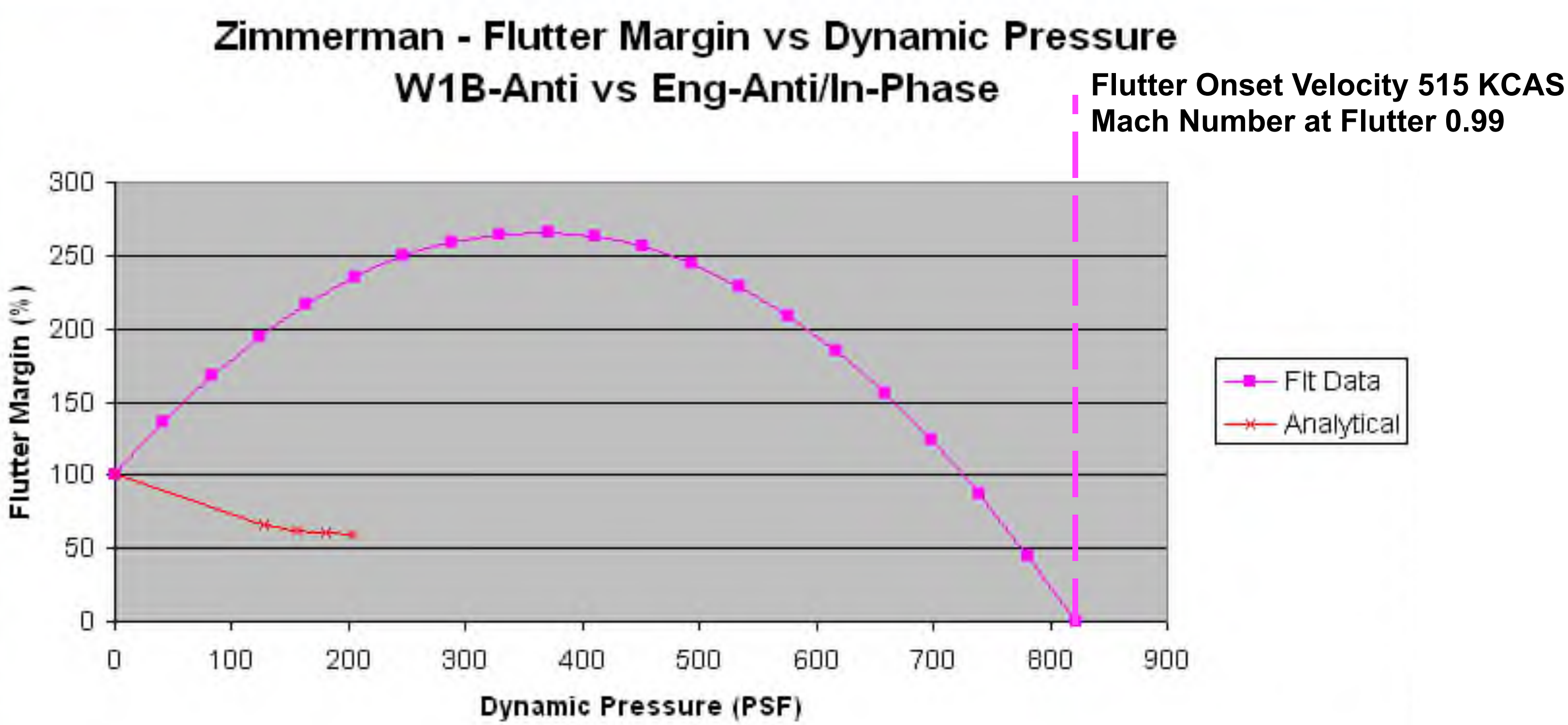
Segment-0 Flight Test Results

- Flutter Raps vs. Analytical Prediction; Example of Ball park Agreement
  - Zimmerman Technique; robust near instability
  - 15,000 ft, Tracking W1B-Anti & W1T-Anti



Segment-0 Flight Test Results

- Flutter Raps vs. Analytical Prediction; Example of Failed Agreement
  - Zimmerman Technique; robust near instability
  - 15,000 ft, Tracking W1B-Anti & Eng-Anti/In-Phase



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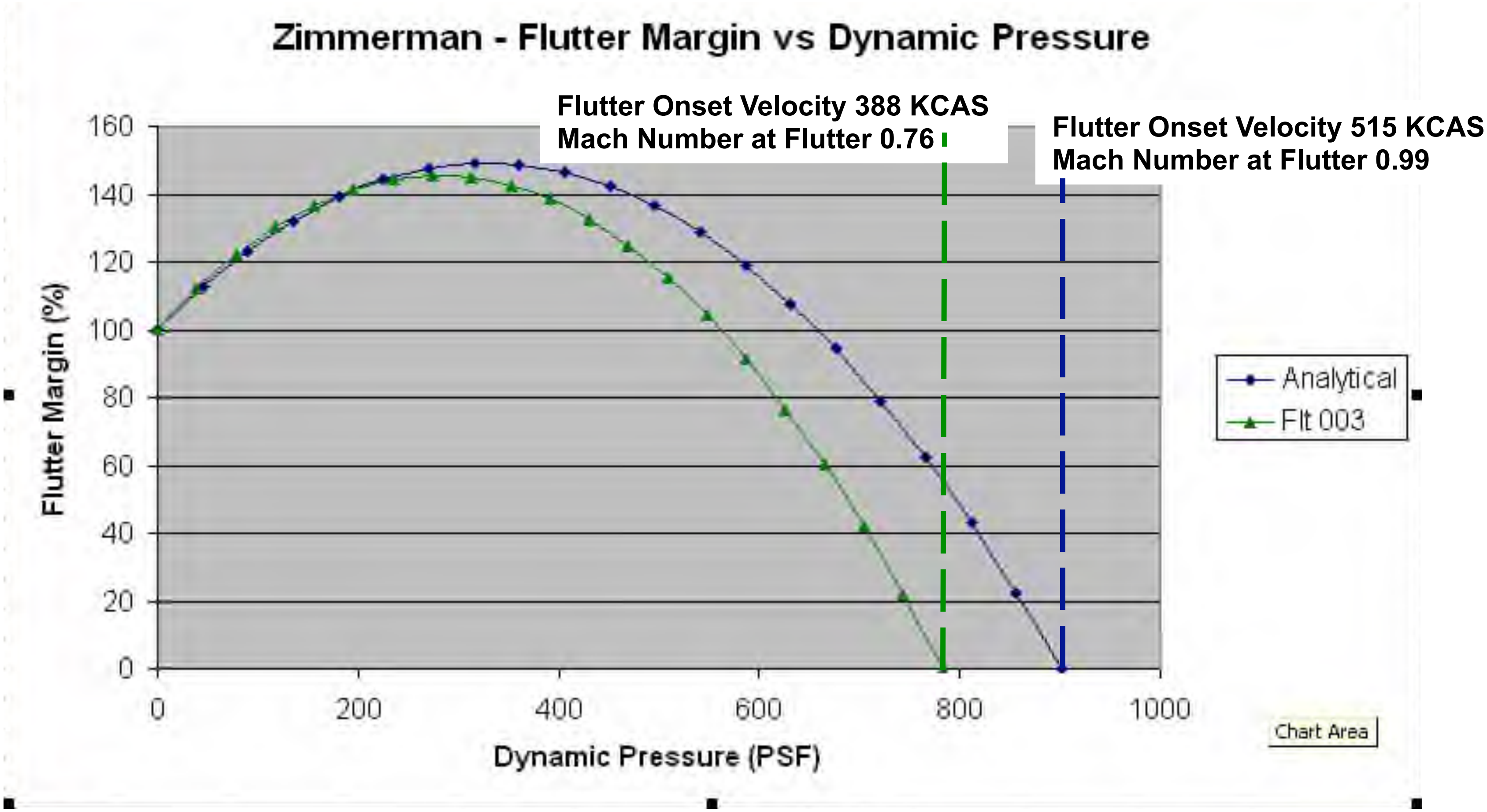
Segment-0 Flight Test Results

- Flutter Raps vs. Analytical Prediction; Example of Good Agreement
  - Zimmerman Technique; robust near instability
  - 15,000 ft, Tracking W1B-Anti & Aft Fuselage Lateral/Torsion



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Closed Door Analysis for Full Envelope

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- Original Flutter Analysis Remains Valid
  - Instability crossings occur only with wing reserve tanks 2 & 3 full (will be empty for initial envelope expansion)
  - Flutter onset not predicted to be explosive but rather relatively moderate; pilot should sense vibrations before major structural damage
- Critical Flutter Margin 1.6 Vd (Dive Velocity - Max. A/C Velocity)
  - Increase over baseline (result of stiffer nacelles; measured in GVT and modeled for analysis)

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Closed Door Analysis for Full Envelope

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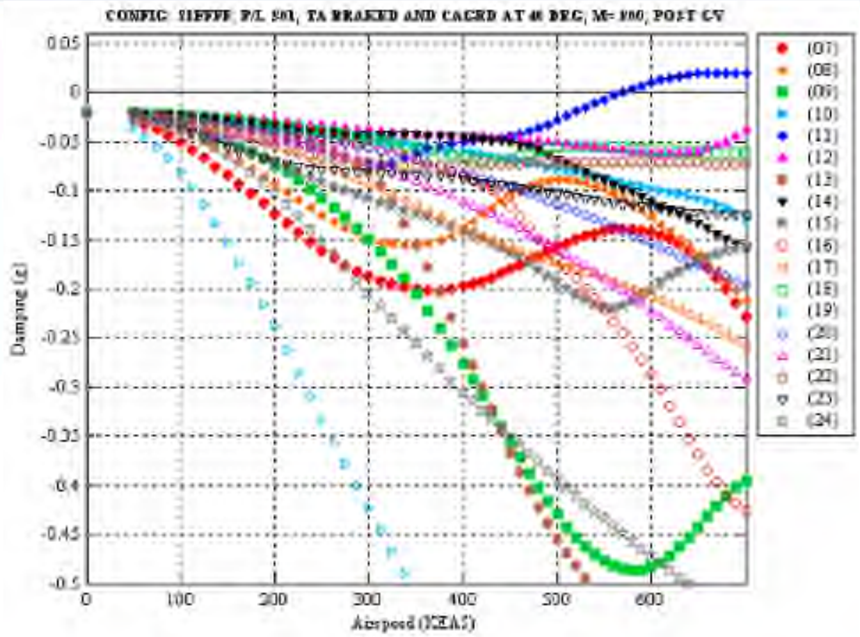
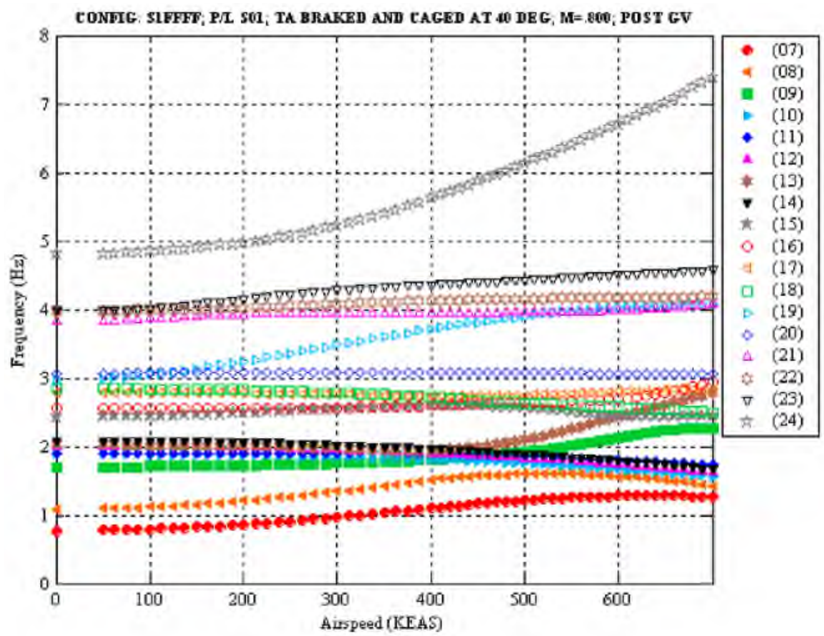




Notes:

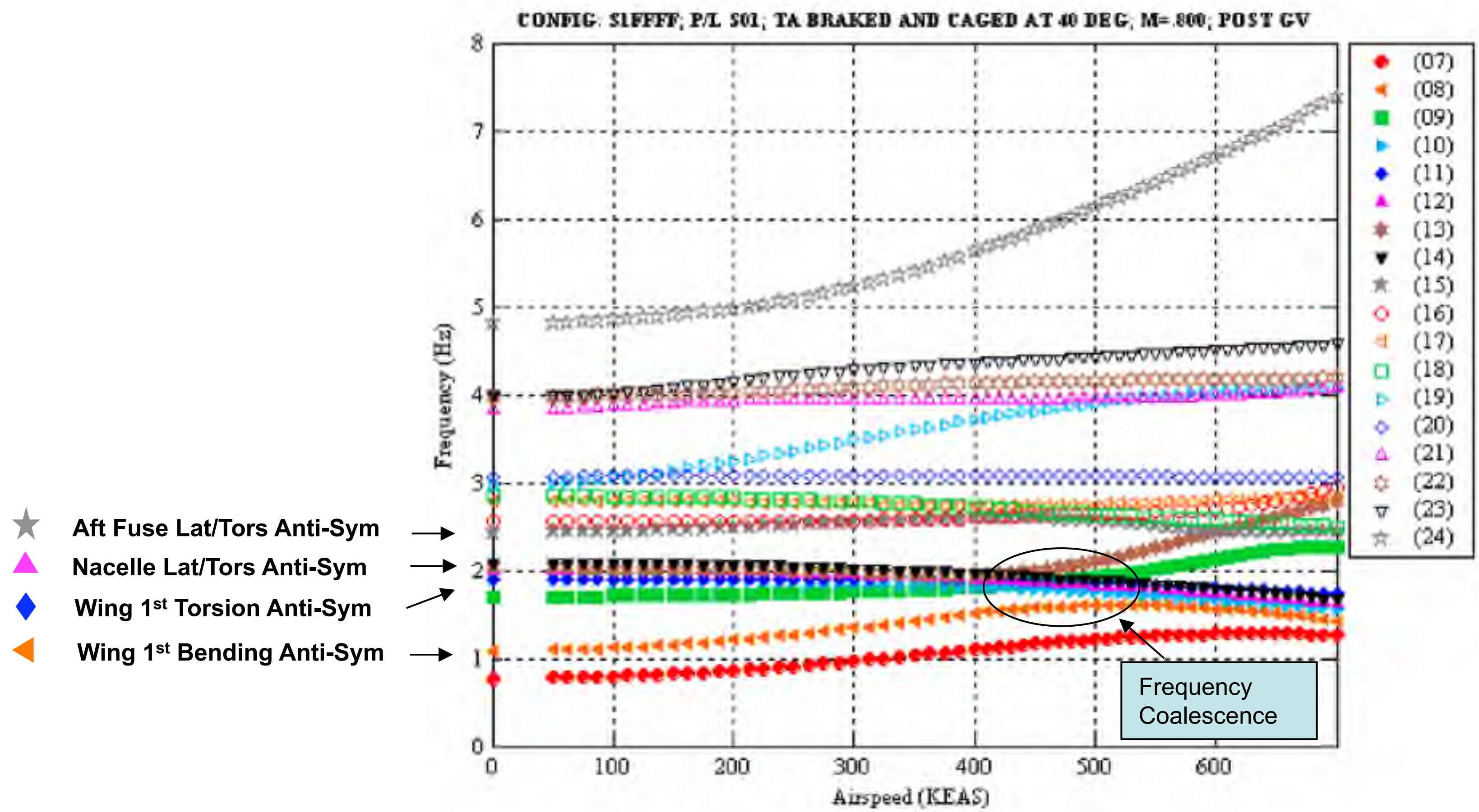
1. For wing reserve tanks 2&3 full, Mach

0.8, post GVT model correlation, TA caged and braked

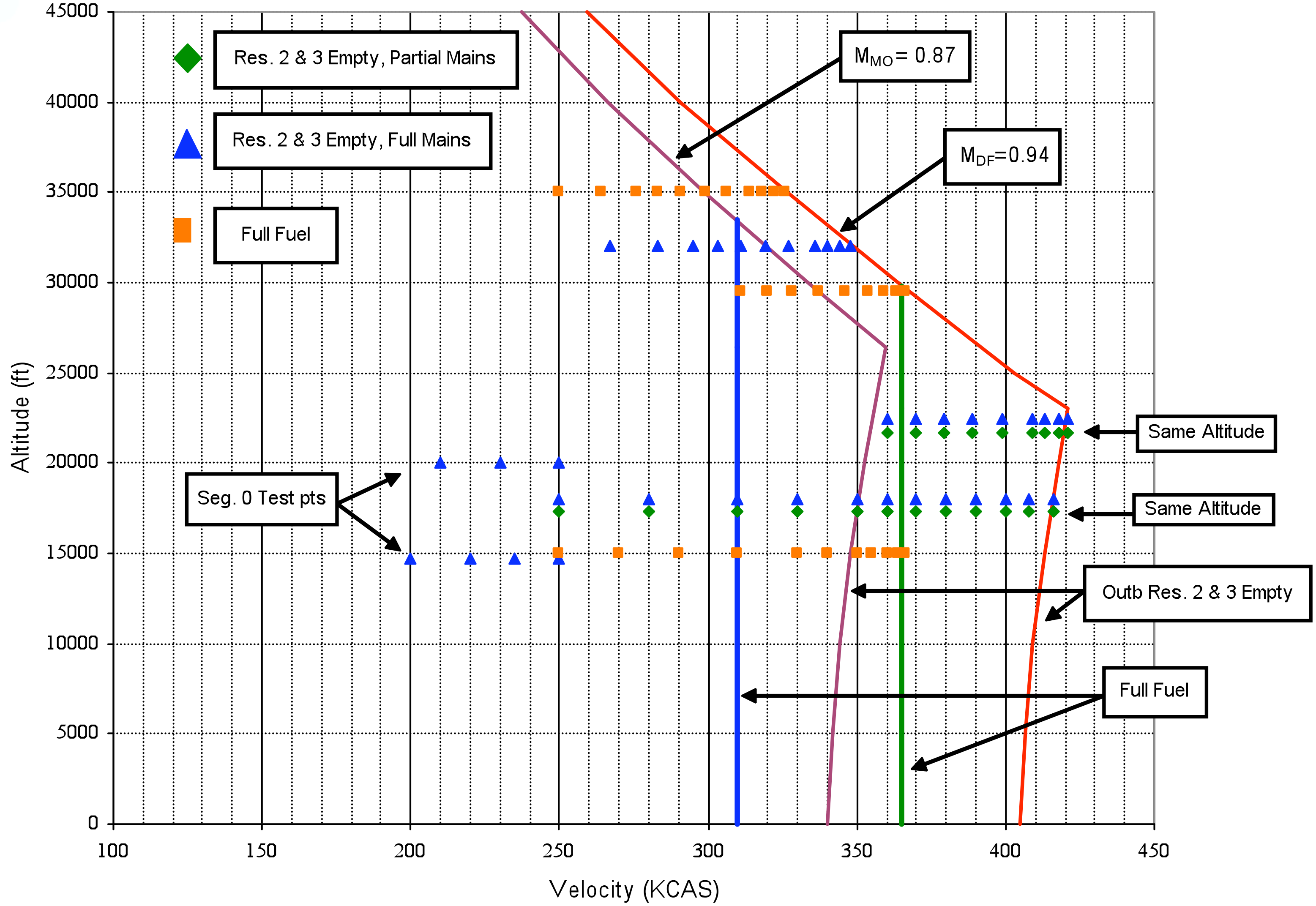
2. Rigid body and remainder of analysis elastic modes not plotted here (60 total, usually up to 20 Hz)

Closed Door Analysis for Full Envelope

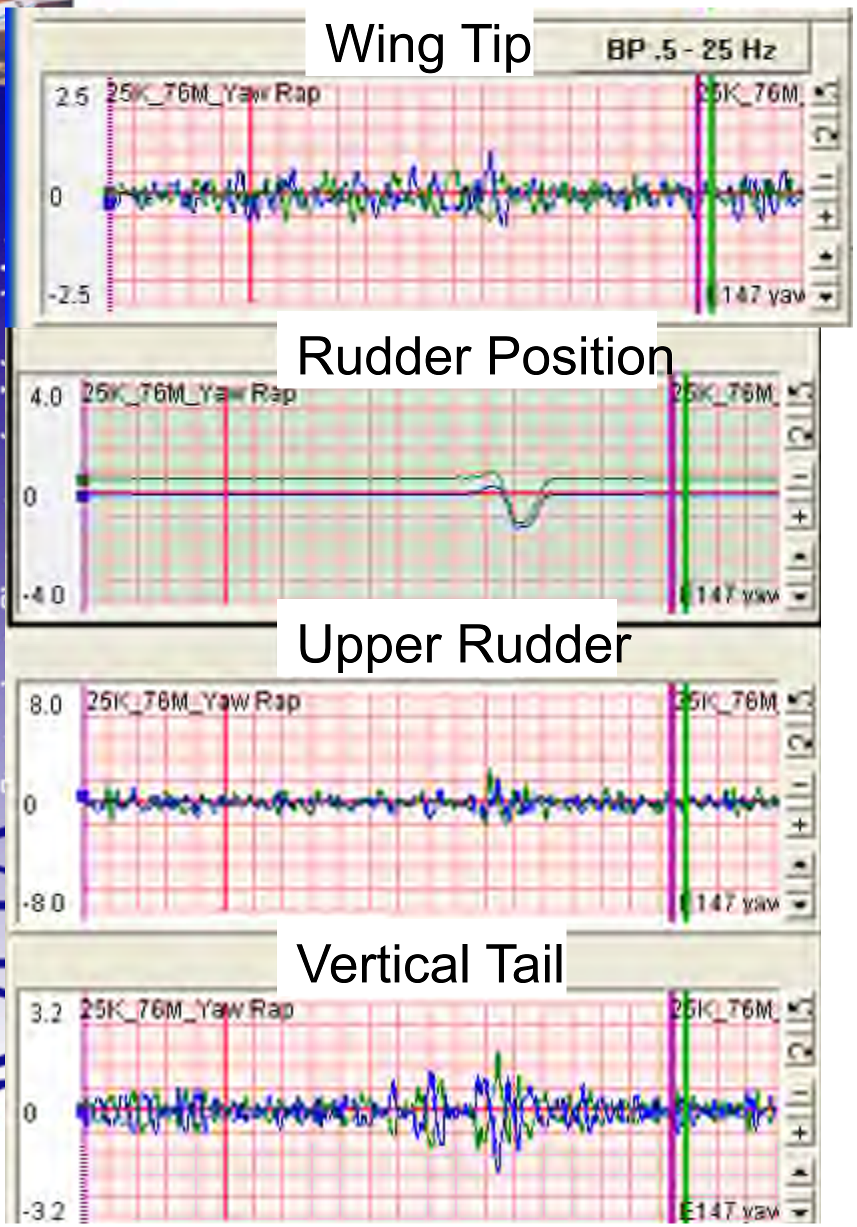
- Predicted Flutter Mechanism
  - Wing first bending, Anti – Sym (1.09 Hz); *major effect on flutter speed*
  - Wing first torsion and Outboard nacelle lateral/roll-pitch, Anti – Sym (1.90 Hz); *major effect on flutter speed*
  - Inboard Nacelle lateral/torsion, Anti – Sym (2.02 Hz)
  - Aft fuselage lateral/torsion and Wing fore/aft, Anti – Sym (2.43 Hz)



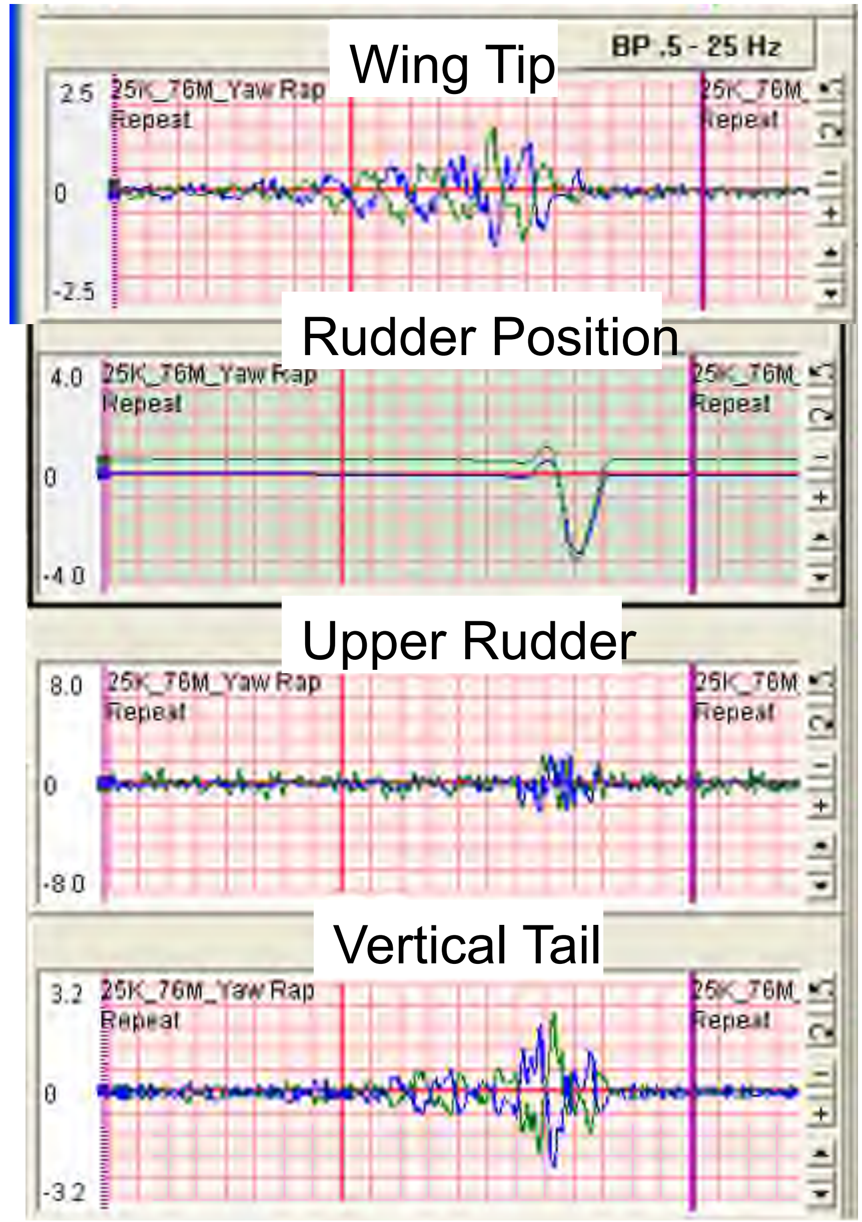
Flight Flutter Envelope Expansion Test Points



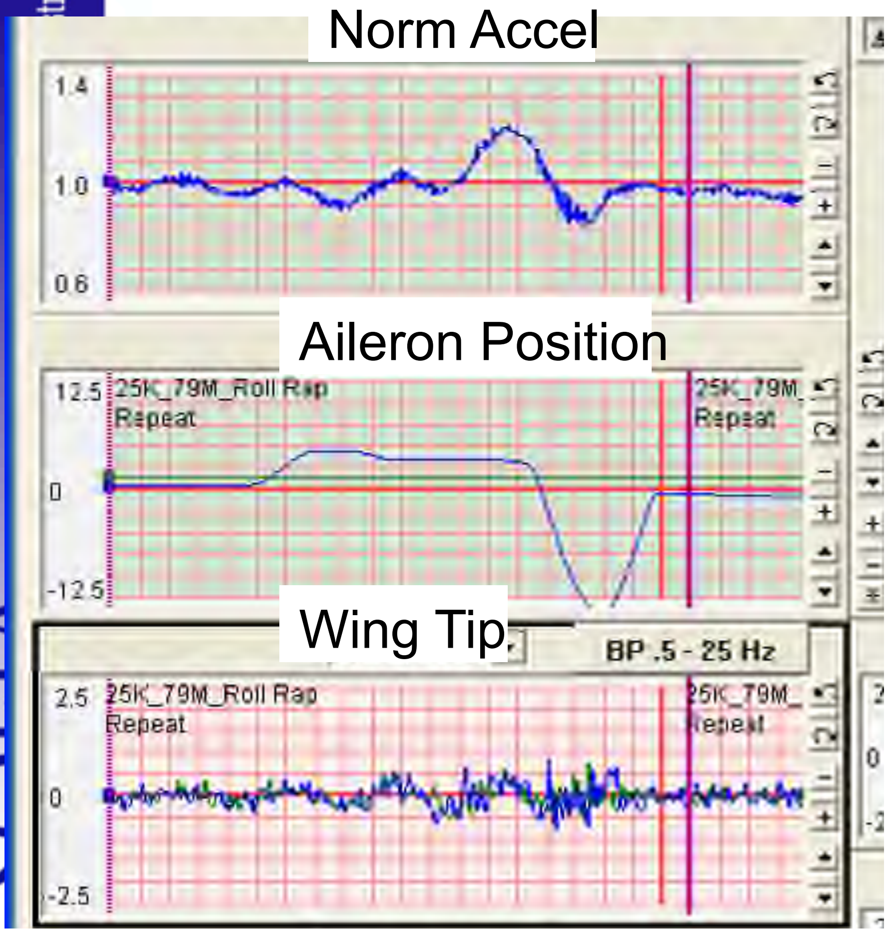
Flt 006 25K ft @ M0.76
First Yaw Rap



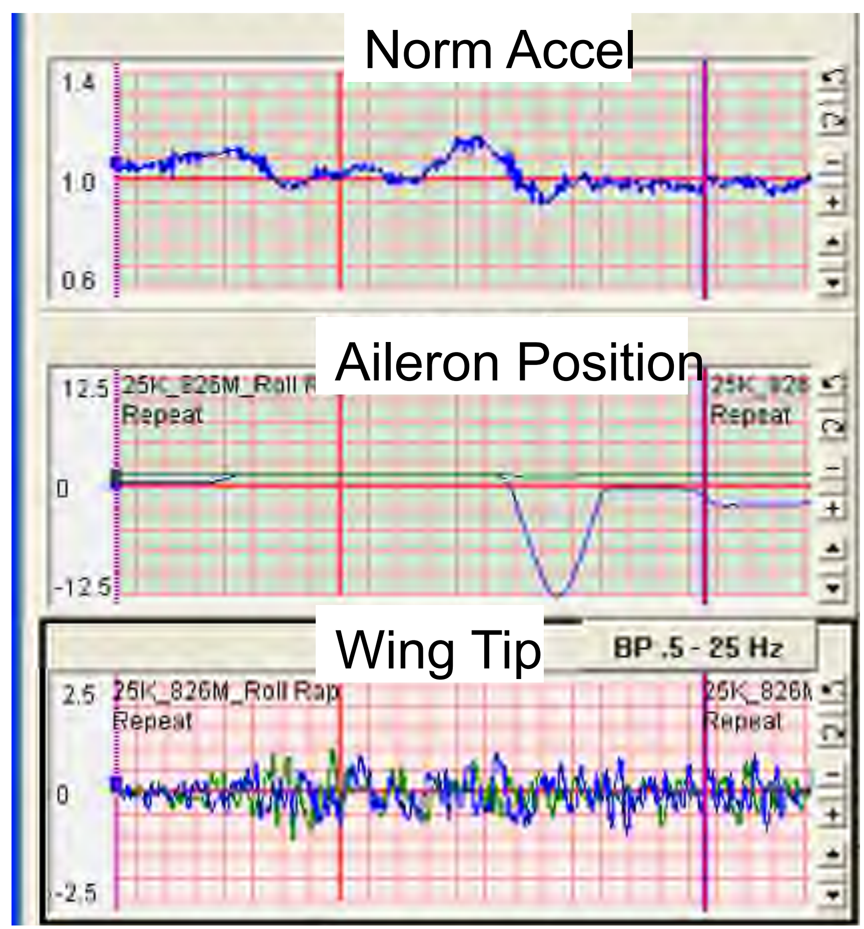
Flt 006 25K ft @ M0.76
Repeat Yaw Rap

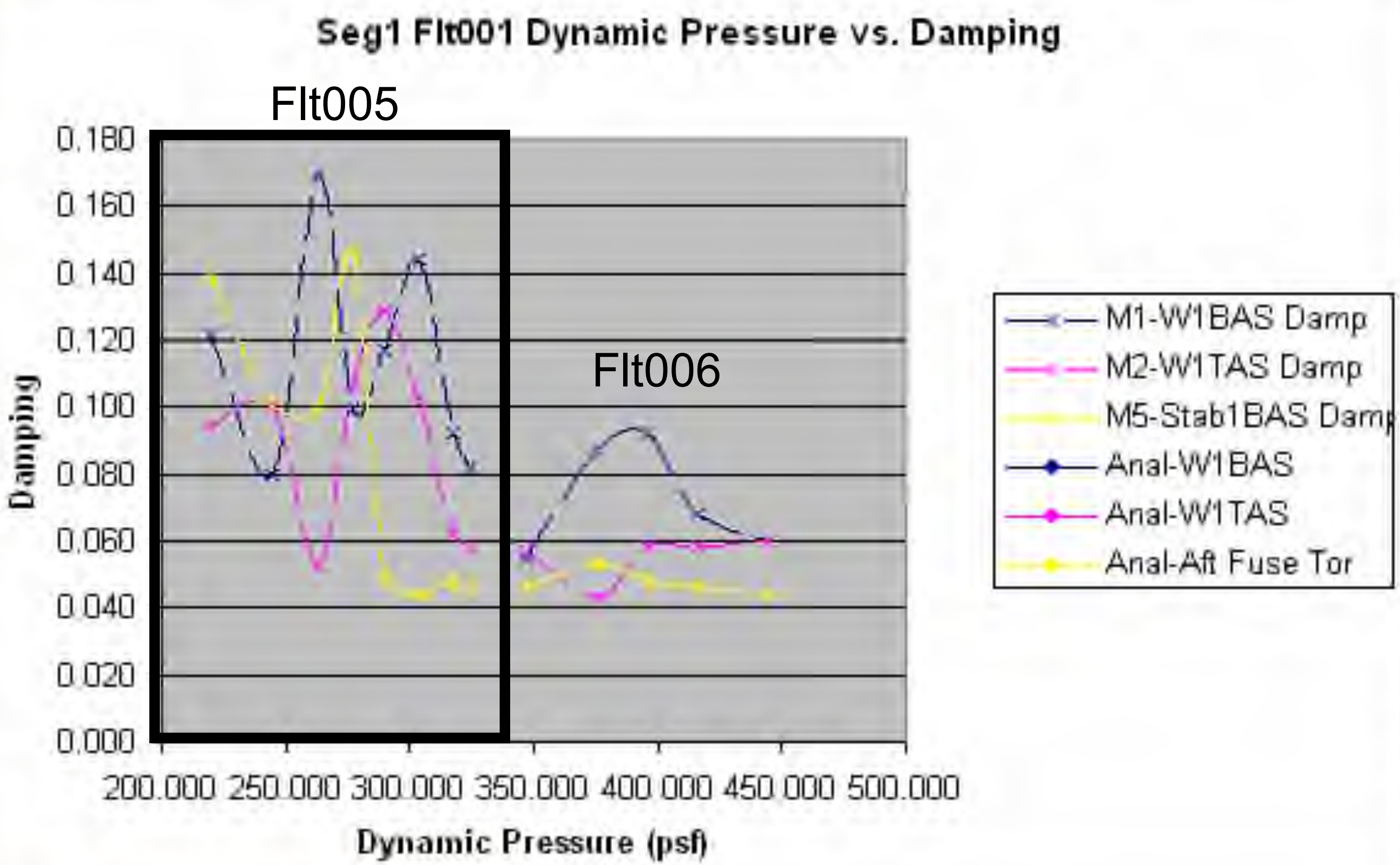


Flt 006 25K ft @ 0.79 Mach
Roll Rap – **No Turbulence**



Flt 006 25K ft @ 0.83 Mach
Roll Rap **- w/ Light Turbulence**




Seg1 Flt001 Dynamic Pressure vs. Damping
Flt005
Flt006
Damping
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
200.000 250.000 300.000 350.000 400.000 450.000 500.000
Dynamic Pressure (psf)
M1-W1BAS Damp
M2-W1TAS Damp
M5-Stab1BAS Damp
Anal-W1BAS
Anal-W1TAS
Anal-Aft Fuse Tor

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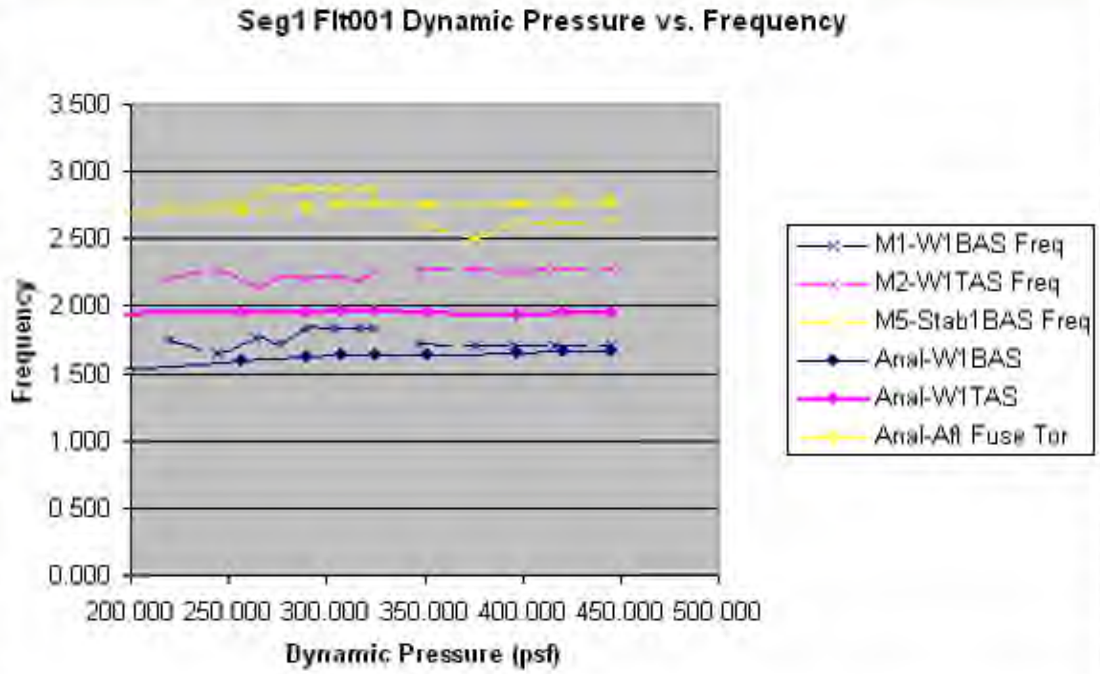

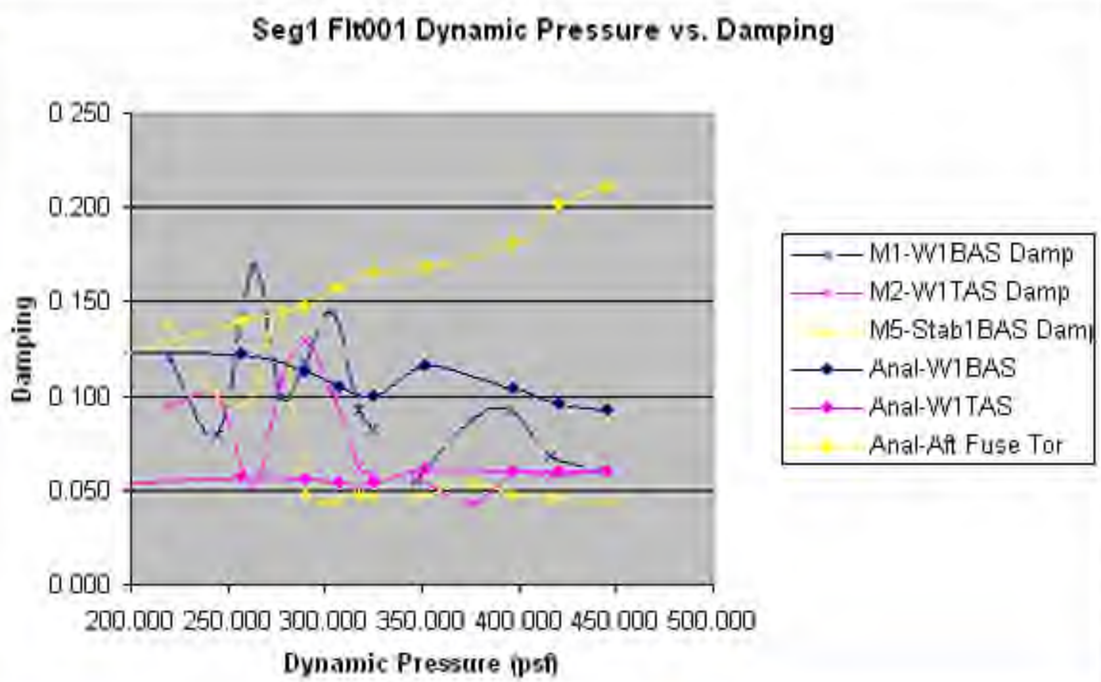

Flutter Envelope Cleared

- !Closed Door Envelope Cleared to Mmo (0.87M) and Vmo (340 KCAS)
  - o! FAR 25.629, Flutter, is Satisfied by Flight Test to Md (0.92M) and Vd (370 KCAS)
    - –! Damping Margin of 0.03 Maintained
    - –! No Large and Rapid Reduction in Damping as Md and Vd are Approached
  - o! FAR 25.1505, Maximum Operating Limit Speed, Also Met by Flight Test
    - –! Level Flight Upset to Dive Margins of 0.05M and 30 KCAS
- ! Short Science Open Door Envelope Cleared to Mmo (0.87M) and Vmo (270 KCAS)
  - o! Open Door Configuration Cleared by Closed Door (Same Flutter Modes)