Overview of the Integrated Adaptive Wing Technology Maturation Wind-tunnel Test Objectives

AIAA SciTech Forum 2024

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January 12, 2024

Outline

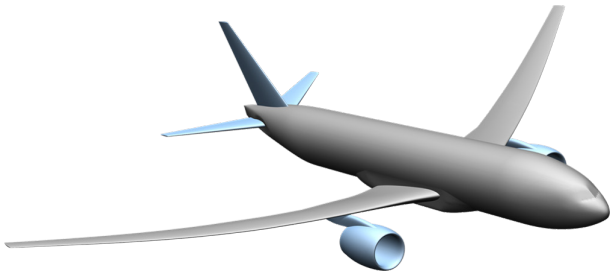
(1) **Introduction and Background**

(2) **Wind-tunnel Test Article**

   a) Design, modeling, and characterization

(3) **Test Plan**

(4) **Questions**

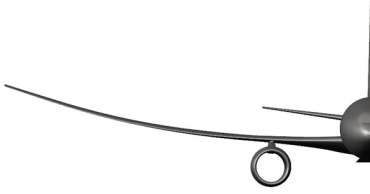


IAWTM Overview

(1) NASA Advanced Air Transport Technology (AATT) project
- Higher Aspect Ratio Optimal Wing technical challenge: Enable a 1.5-2X increase in the aspect ratio of a lightweight wing with safe flight control and structures

(2) Approach
- Cooperative agreement between NASA and Boeing to develop and test control technologies to meet multiple objectives:
  - Drag optimization
  - Maneuver load alleviation
  - Gust load alleviation
  - Flutter suppression

(3) Purpose
- Decrease cost of vehicle operation by reducing induced drag and structural weight penalties normally associated with a high-aspect ratio wing



(4) IAWTM vehicle
- Aspect ratio 13.5 wing of a modern transport configuration based on the Common Research Model (CRM)
- Aspect ratio is a 1.5X increase over the nominal aspect ratio 9 CRM wing

(5) Analysis and testing
- Full-scale analysis
  - Evaluation of performance using a high fidelity 6DOF simulation and development of multiobjective control law
- Model-scale testing
  - Wind tunnel test to be conducted at the NASA Langley Transonic Dynamics Tunnel (TDT)
  - Two phases (open- and closed-loop), each 18 days

Test Objectives

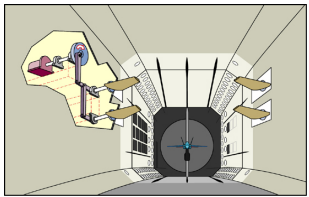
(1) Drag optimization at off nominal conditions
- Drag measured with balance (5-component)

(2) Maneuver load alleviation
- Load reduction measured with model strain sensors

(3) Gust load alleviation
- Gust excitation provided by TDT airstream oscillation system (AOS)
- Upstream vane sensor to serve as surrogate LIDAR gust detector for predictive gust load alleviation

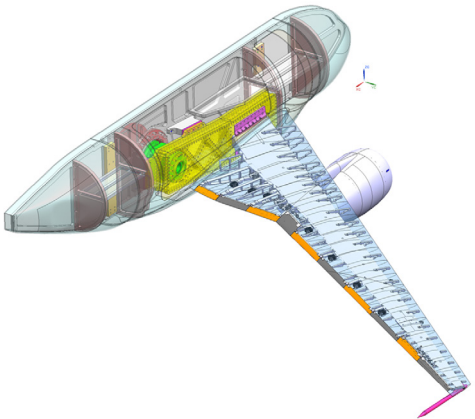
(4) Active flutter suppression
- Modal suppression important at all operating conditions due to low structural stiffness and damping

TDT AOS



Wind-tunnel Test Article Overview

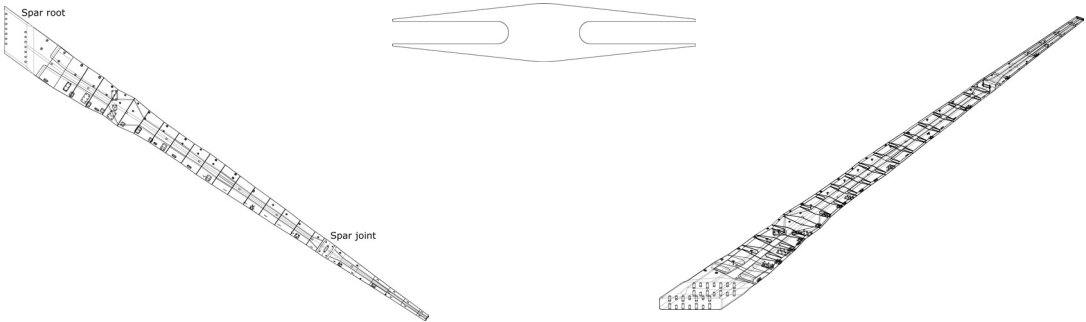
- Semispan dynamically scaled wing for testing at NASA Transonic Dynamics Tunnel (TDT)
  - Spar-pod construction (aluminum spar, carbon fiber skins) with flow-through engine nacelle and nonmetric fuselage
  - 10 active control surfaces and large number of sensors (accelerometers, strain gages, distributed strain sensors, balance, gust vane sensor)
- Removable tip ballast designed to lower the flutter frequency and dynamic pressure for AFS testing



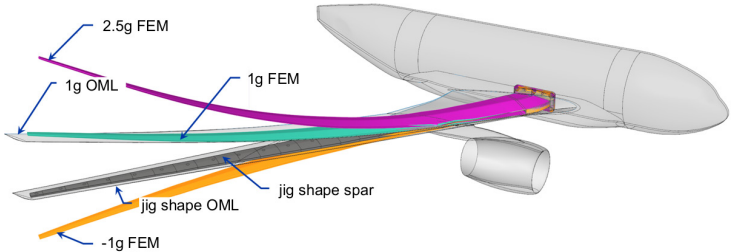
Source: D. Ortega, Boeing, *AWT04 Modal Correlated FEM Review*

Spar Design

- Equivalent beam model provided target spanwise bending and torsional stiffness distributions
  - Modified I-beam cross section developed to improve stiffness matching and remain inside the wing OML
  - 25 equally distributed spanwise design stations used for stiffness matching, with linear taper between those cross sections
- Due to spar length, fabricated in two pieces and permanently bonded and fastened at spar joint

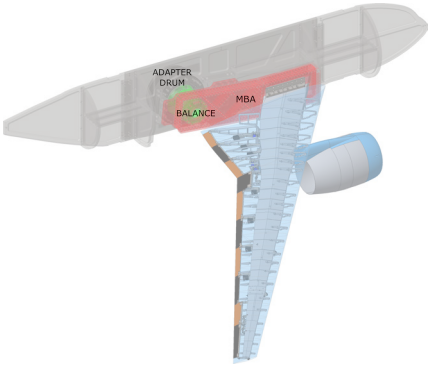


- Equivalent beam deformations (FEM) for several critical flight conditions illustrate representative static aeroelastic deformation of the model

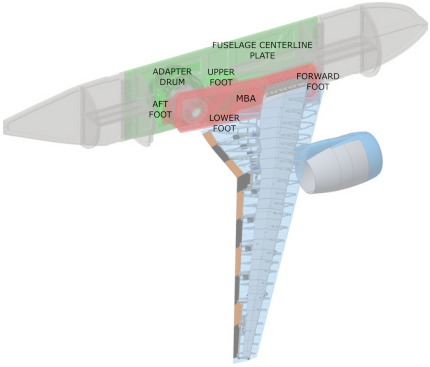


Balance Adapter Design

- To support both aerodynamic performance data acquisition using a balance and dynamic aeroelastic testing, a balance adapter will be used to engage/disengage the balance on the model load path



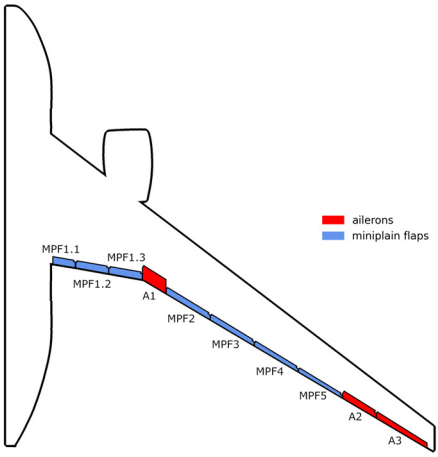
Shims-off configuration



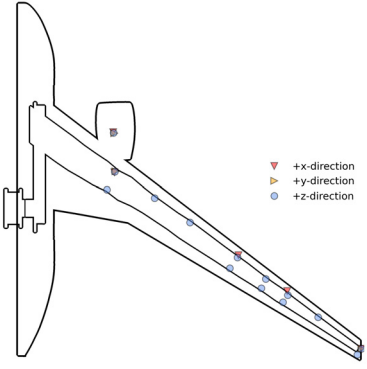
Shims-on configuration

Control Surfaces

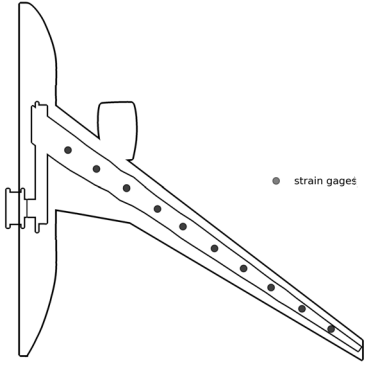
- 10 trailing edge distributed control surfaces
  - 3 hydraulically actuated ailerons (faster response)
  - 7 electric servo-actuated miniplain flaps (slower response)



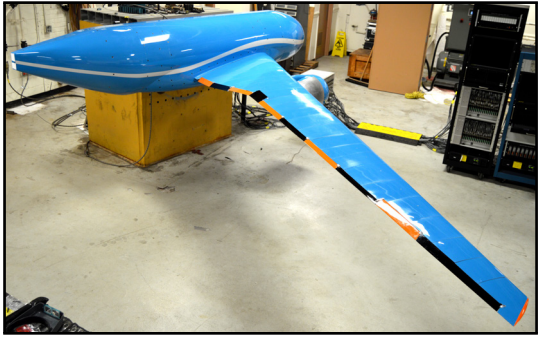
- Sensors: 3 triaxial and 13 single axis accelerometers, 10 full-bridge strain gages, Q-flex inclinometer, 8 balance-based loads, gust vane sensor



Accelerometers



Strain gages



Source: NASA

Pretest Analytical Work

(1) Tools
- FUN3D
- VSPAERO
- MSC Nastran
- Simulink
- ZAERO

(2) Studies
- Gust vane modeling
- Control surface aerodynamic database
- Flutter boundary
- Development of ASE models
- Buffet onset
- Critical Mach number
- Wind tunnel wall interference modeling
- Control surface reversal boundary
- Closed-loop controllers developed by Boeing and NASA

Model Characterization

(1) Ground vibration test
   - TDT model preparation area, mounted to backstop
   - TDT test section, mounted to tunnel sidewall support

(2) Measured mass properties database

(3) Actuator checkout and performance characterization

(4) Static load testing
   - Strain gage calibration, model validation, digital image correlation checkout

Backstop GVT

(1) GVT in TDT MPA of three model configurations
   - Shims-off
   - Shims-on
   - Shims-on, ballast-on

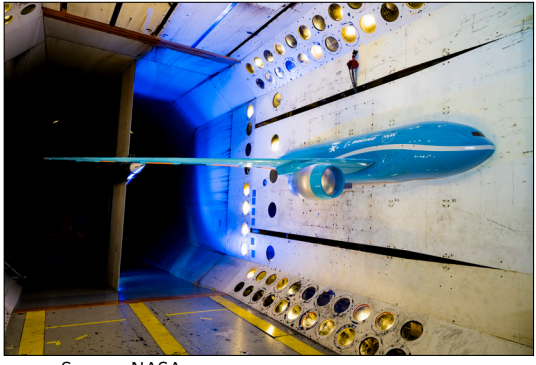
(2) Several other parameters were varied during testing to assess modal impact
   - Control surfaces taped OR actuators on
   - Skin pods untaped OR taped
   - Shaker OR hammer excitation

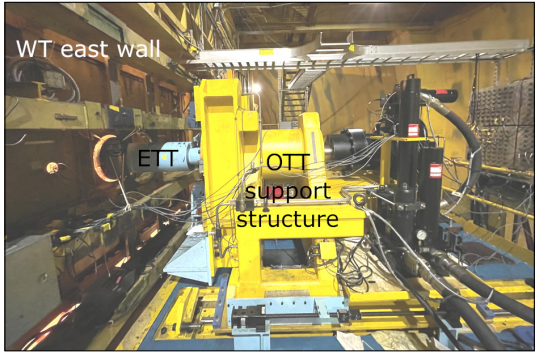
(3) Equipment
   - 3x shakers
   - Impact hammer
   - >100 externally-instrumented accelerometer signals

Source: NASA

Test Section GVT

- After MPA GVT, most significant structural uncertainty is associated with test section boundary condition, with the test article mounted to the sidewall support



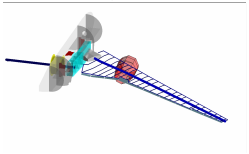


Source: NASA

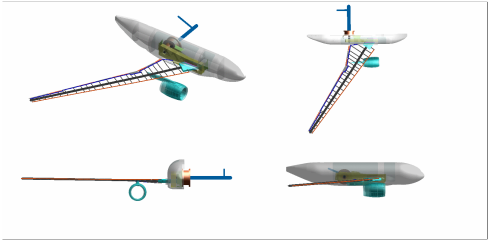
FEM Normal Modes Comparison

Shims-off configuration, first vertical bending

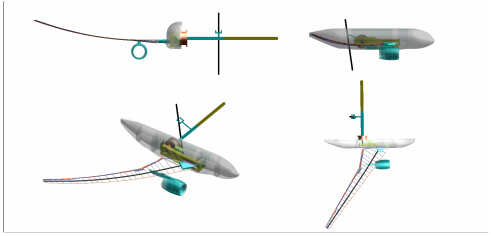
AWT03, 3.573 Hz



AWT04, 3.635 Hz



AWT05, 3.644 Hz (3.59 Hz test)

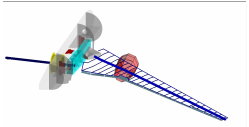


Source: D. Ortega, Boeing, *AWT03 ASE State-Space Modeling*, *AWT04 Modal Correlated FEM Review*, and *AWT05 GVT2 in TDT Modal Correlation FEM Review*

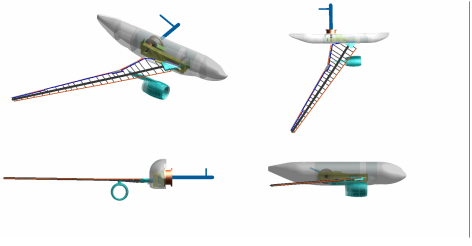
FEM Normal Modes Comparison

Shims-off configuration, vehicle pitch

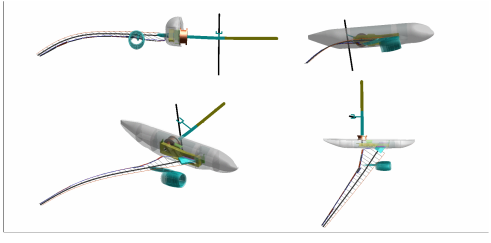
AWT03, 7.308 Hz



AWT04, 7.674 Hz



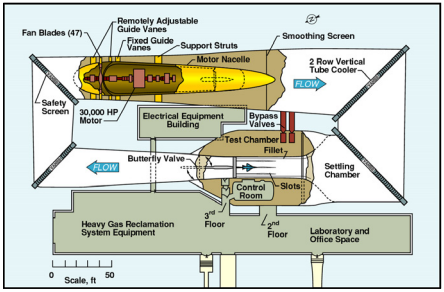
AWT05, 8.488 Hz (8.78 Hz test)



Source: D. Ortega, Boeing, *AWT03 ASE State-Space Modeling*, *AWT04 Modal Correlated FEM Review*, and *AWT05 GVT2 in TDT Modal Correlation FEM Review*

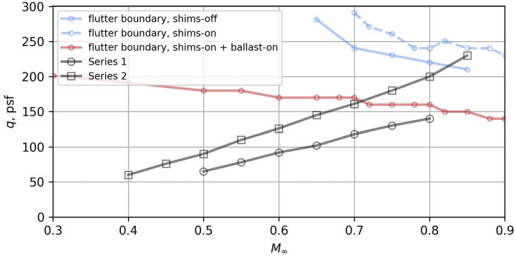
NASA Langley Transonic Dynamics Tunnel

- TDT is a unique WT facility that contains several features essential for aeroservoelastic testing
  - Configured to perform higher risk aeroelastic testing
    - Direct view of the test article from the control room
    - Bypass valves that can rapidly lower test section dynamic pressure in the case of an instability
    - Downstream safety screen to protect the drive motor and fan blades
  - Hydraulic power supply for the test article available for high speed actuation of control surfaces
  - Airstream oscillation system with upstream gust vanes to provide gust excitation for GLA testing
  - Heavy gas (R134a) test medium to match fluid-structure scaling parameters important to aeroelastic response and flutter



Source: NASA

- Phase 1 testing will target open-loop aerodynamic and aeroelastic characterization
  - Each series corresponds to a different initial wind-off pressure
  - At each point, control surface static schedules and dynamic sweeps will be conducted for aerodynamic model verification and updating
    - Data is also planned to be acquired at several test article AOAs and multiple surfaces active for interaction testing
- Flutter mechanism for shims-off and shims-on configurations is a hump mode, and since the as-built model structural damping is quite low, real-time monitoring will be essential



Summary

- IAWTM wind-tunnel test article has been designed to meet test objectives targeting active control techniques for a highly flexible, high aspect ratio, wing
  - Overview of model scaling, structural design, instrumentation, and control systems demonstrates the complexity of the test article
- Significant pretest analysis and characterization work has been completed in preparation for Phase 1 open-loop testing
- Lessons learned and data acquired during the preparation and conduct of the wind tunnel experiment will be directly applicable to improvements in aeroelastic modeling and testing of high aspect ratio, highly flexible wings

Acknowledgments

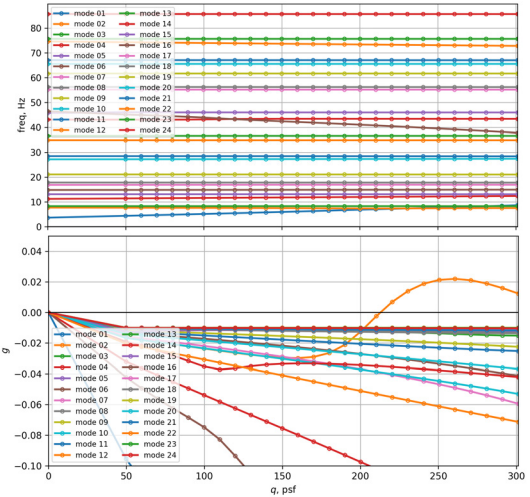
Special thanks to IAWTM team members from Boeing Research & Technology, NextGen Aeronautics, NASA Langley Research Center, NASA Ames Research Center, and NASA Armstrong Flight Research Center

Questions?

Example Pretest Flutter Analysis, $M_\infty = 0.85$

Shims-off configuration

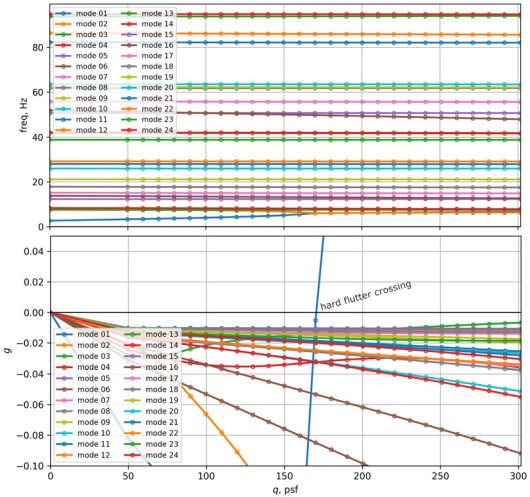
- Hump flutter mechanism occurs at $q_\infty \approx 212$ psf with a flutter frequency of $f \approx 7.35$ Hz



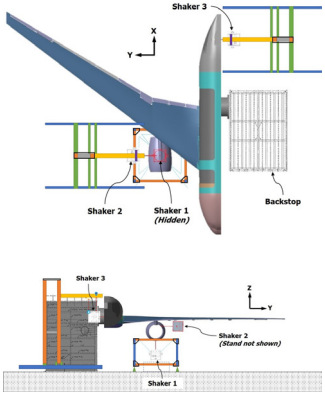
Example Pretest Flutter Analysis, $M_\infty = 0.70$

Shims-on, ballast-on configuration

- Hard flutter mechanism occurs at $q_\infty \approx 170$ psf with a flutter frequency of $f \approx 6.01$ Hz



Backstop GVT

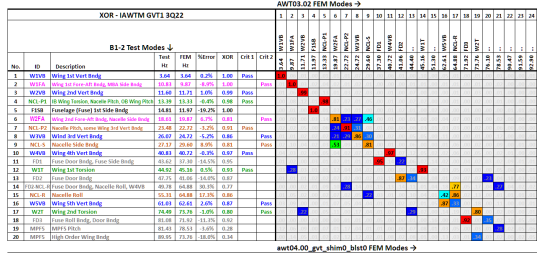


Source: J. Templeton, NASA LaRC, *GVT Test Plan*

Backstop Model Modes Pre- and Post-FEM Scrub

Shims-off configuration

- Pre- and post-FEM scrub tables summarizing frequency error and cross-orthogonality between FEM and test modes
  - Scrub led to significant improvements in XOR and frequency matching
- Planned configuration for drag optimization testing



Source: D. Ortega, Boeing, *AWT04 Modal Correlated FEM Review*

Backstop Model Modes Pre- and Post-FEM Scrub

Shims-on configuration

- Planned configuration for MLA and GLA testing

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XOR - IAWTM GVT1 3Q22

B2-2 Test Modes ↓

No.	ID	Description	Test Hz	FEM Hz	%Error	XOR	Crit 1	Crit 2
1	W1VB	Wing 1st Vert Bndg	3.65	3.67	0.5%	1.00	Pass	
2	W1FA	Wing 1st Fore-Aft Bndg, Fuse Side Bndg	11.40	10.80	-5.0%	0.99	Pass	
3	W2VB	Wing 2nd Vert Bndg	11.73	11.97	2.0%	0.98	Pass	
4	NCL-P1	IB Wing Torsion, Nacelle Pitch, OB Wing Pitch	14.66	14.90	1.7%	0.98	Pass	
5	NCL-S	Nacelle Side Bndg	19.21	19.75	2.8%	0.71		
6	W2FA	Wing 2nd Fore-Aft Bndg, Fuse 1st Side B	26.49	19.75	-10.3%	0.71		
7	W3VB	Wing 3rd Vert Bndg	25.24	27.83	10.2%	0.68		
8	W4VB	Wing 4th Vert Bndg	40.32	39.46	-2.1%	0.81		Pass
9	W3FA	Wing 3rd Fore-Aft Bndg, Fuse 1st Side B	44.91	41.13	-8.5%	0.87		Pass
10	W1T	Wing 1st Torsion	45.01	45.30	0.6%	0.72		
11	F1SB	Fuse Side & Roll Bndg	49.90	44.45	-10.9%	0.70		
12	NCL-R	Nacelle Roll	53.84	64.64	20.0%	0.83		
13	ncl.n.wtvs	Nacelle Roll, Wing 5th Vert Bndg	59.09	52.66	-10.9%	0.70		
14	W5VB	Wing 5th Vert Bndg	66.04	64.43	-2.4%	0.81		Pass
15	W2T	Wing 2nd Torsion	74.45	73.48	-1.3%	0.64		
16	MPF5	MPF5 Pitch	80.00	75.76	-5.3%	0.61		

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XOR - IAWTM GVT1 3Q22

B2-2 Test Modes ↓

No.	ID	Description	Test Hz	FEM Hz	%Error	XOR	Crit 1	Crit 2
1	W1VB	Wing 1st Vert Bndg	3.65	3.70	1.2%	1.00	Pass	
2	W1FA	Wing 1st Fore-Aft Bndg, Fuse Side Bndg	11.40	11.38	-1.1%	0.99	Pass	
3	W2VB	Wing 2nd Vert Bndg	11.73	12.02	2.4%	0.99	Pass	
4	NCL-P1	IB Wing Torsion, Nacelle Pitch, OB Wing Pitch	14.66	14.06	-4.1%	0.99	Pass	
5	NCL-S	Nacelle Side Bndg	19.21	19.91	3.6%	0.97	Pass	
6	W2FA	Wing 2nd Fore-Aft Bndg, Fuse 1st Side B	26.49	26.88	1.5%	0.96	Pass	
7	W3VB	Wing 3rd Vert Bndg	25.24	25.90	2.6%	0.95	Pass	
8	W4VB	Wing 4th Vert Bndg	40.32	41.18	2.1%	0.98	Pass	
9	W3FA	Wing 3rd Fore-Aft Bndg, Fuse 1st Side B	44.91	42.58	-5.2%	0.97		Pass
10	W1T	Wing 1st Torsion	45.01	45.95	2.1%	0.92	Pass	
11	F1SB	Fuse Side & Roll Bndg	49.90	48.34	-3.1%	0.96	Pass	
12	NCL-R	Nacelle Roll	53.84	54.27	0.8%	0.95	Pass	
13	ncl.n.wtvs	Nacelle Roll, Wing 5th Vert Bndg	59.09	58.43	-1.1%	0.86		Pass
14	W5VB	Wing 5th Vert Bndg	66.04	65.92	-0.2%	0.90	Pass	
15	W2T	Wing 2nd Torsion	74.45	74.19	-0.3%	0.80	Pass	
16	MPF5	MPF5 Pitch	80.00	78.14	-2.3%	0.85		Pass

Source: D. Ortega, Boeing, *AWT04 Modal Correlated FEM Review*

Backstop Model Modes Pre- and Post-FEM Scrub

Shims-on, ballast-on configuration

- Planned configuration for flutter suppression testing

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XOR - IAWTM GVT1 3Q22

B3-2 Test Modes ↓

No.	ID	Description	Test Hz	FEM Hz	%Error	XOR	Crit 1	Crit 2
1	W1VB	Wing 1st Vert Bndg	2.70	2.68	-0.8%	1.00	Pass	
2	BP1	Ballast Pitch, OB Wing Torsion	8.23	7.92	-3.8%	0.97	Pass	
3	W1FA	Wing 1st Fore-Aft Bndg, MBck Side Bndg	9.07	8.60	-5.2%	0.98		Pass
4	NCL-P1	Nacelle Pitch, Wing Pitch, some Wing 2nd	14.62	14.87	1.7%	0.97	Pass	
5	BP2-W2VB	Ballast Pitch, Wing 2nd Vert Bndg, OB W	15.52	13.84	-10.8%	0.97		
6	W2FA-F1SB	Wing 2nd Fore-Aft Bndg, Fuse 1st Side B	18.17	17.45	-4.0%	0.84		Pass
7	NCL-S	Nacelle Side Bndg	22.76	27.25	19.8%	0.78		
8	W3VB	Wind 3rd Vert Bndg	24.44	23.05	-5.7%	0.92		Pass
9	BT1	Ballast Yaw, OB Wing Fore-Aft Bndg	33.33	29.53	-11.4%	0.96		
10	W4VB	Wing 4th Vert Bndg	38.10	37.49	-1.6%	0.95	Pass	
11	W3FA-F1SB	Wing 3rd Fore-Aft Bndg, Fuse 1st Side B	49.05	42.84	-12.7%	0.93		
12	OBW2T	OB W2hd 2nd Torsion, some Ballast Pitch	49.97	50.64	1.4%	0.90	Pass	
13	NCL-R	Nacelle Roll	52.68	65.55	24.4%	0.76		
14	W5VB	Wing 5th Vert Bndg	56.18	62.18	10.7%	0.59		

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XOR - IAWTM GVT1 3Q22

B3-2 Test Modes ↓

No.	ID	Description	Test Hz	FEM Hz	%Error	XOR	Crit 1	Crit 2
1	W1VB	Wing 1st Vert Bndg	2.70	2.70	-0.1%	1.00	Pass	
2	BP1	Ballast Pitch, OB Wing Torsion	8.23	8.20	-0.4%	0.98	Pass	
3	W1FA	Wing 1st Fore-Aft Bndg, MBck Side Bndg	9.07	8.86	-2.3%	0.98	Pass	
4	NCL-P1	Nacelle Pitch, Wing Pitch, some Wing 2nd	14.62	14.04	-4.0%	0.98	Pass	
5	BP2-W2VB	Ballast Pitch, Wing 2nd Vert Bndg, OB W	15.52	15.31	-1.3%	0.98	Pass	
6	W2FA-F1SB	Wing 2nd Fore-Aft Bndg, Fuse 1st Side B	18.17	18.55	2.1%	0.97	Pass	
7	NCL-S	Nacelle Side Bndg	22.76	23.43	3.0%	0.94	Pass	
8	W3VB	Wind 3rd Vert Bndg	24.44	24.69	1.1%	0.95	Pass	
9	BT1	Ballast Yaw, OB Wing Fore-Aft Bndg	33.33	31.38	-5.9%	0.96	Pass	
10	W4VB	Wing 4th Vert Bndg	38.10	39.18	2.8%	0.97	Pass	
11	W3FA-F1SB	Wing 3rd Fore-Aft Bndg, Fuse 1st Side B	49.05	47.22	-3.7%	0.95	Pass	
12	OBW2T	OB W2hd 2nd Torsion, some Ballast Pitch	49.97	51.68	3.4%	0.89	Pass	
13	NCL-R	Nacelle Roll	52.68	53.04	0.7%	0.91	Pass	
14	W5VB	Wing 5th Vert Bndg	56.18	56.68	0.9%	0.86*	Pass	

Source: D. Ortega, Boeing, *AWT04 Modal Correlated FEM Review*

Test Section Model Modes, Configurations 1 and 2

Backstop GVT-calibrated model

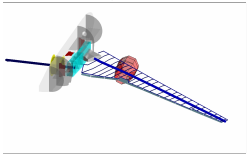
Shim Off (B1)		Shim On (B2)			
No.	Freq	No.	Freq	ID	Description
1	3.63	1	3.65	W1VB	Wing 1st Vert Bndg
2	7.67	2	7.92	VP	Vehicle Pitch
3	8.28	3	8.45	W1FA	Wing 1st Fore-Aft Bndg, Vehicle 1st Fore-Aft Bndg
4	11.20	4	11.25	W2VB	Wing 2nd Vert Bndg
5	13.11			F1SB	Fuse 1st Side Bndg, Wing 1st Fore-Aft Bndg
6	14.80	5	14.93	NCL-P1	IB Wing Torsion, Nacelle Pitch, Wind 2nd Vert Bndg IP
7	16.85	7	17.12	NCL-P2	IB Wing Torsion, Nacelle Pitch, Wind 2nd Vert Bndg OOP
8	17.80	6	15.19	W2FA	Wing 2nd Fore-Aft Bndg
9	21.07	8	21.14	NCL-S1	Nacelle Side Bndg
10	27.16	9	27.69	W3VB	Wing 3rd Vert Bndg
11	28.45	10	28.72	ETT-AX	ETT Struct Axial, Nacelle Side Bndg
12	34.87			F1RB	Fuse Roll Bndg, MBA Pitch, W2FA
13	36.61	11	36.53	W3FA1	Wing 3rd Fore-Aft Bndg, Fuse Side Bndg OOP
		12	43.12	W3FA2	Wing 3rd Fore-Aft Bndg, Fuse Side Bndg IP
14	43.08	13	43.95	W4VB	Wing 4th Vert Bndg
15	45.73			W3FA-W1T	Wing 3rd Fore-Aft Bndg, Wing 1st Torsion
16	46.44	14	46.35	W1T	Wing 1st Torsion
17	55.17	15	55.45	NCL-R1	Nacelle Roll, W3FA In-Phase (IP)
		16	57.20	F2SB	Fuse 2nd Side Bndg, W3FA
18	56.24			NCL-R2	Nacelle Roll, W3FA Out-of-Phase (OOP)
19	61.67	17	61.80	FD1	Fuse Main Door Bndg
20	65.55	18	65.27	W5VB	Wing 5th Vert Bndg
21	67.08			W5VB-F1RB	Wing 5th Vert Bndg, Fuse Roll Bndg
22	74.60	19	74.56	W2T	Wing 2nd Torsion
23	75.65			ETT-FA	ETT Struct Fore-Aft Bndg
24	85.68	20	80.03	W4FA	Wing 4th Fore-Aft Bndg
		21	91.20	W4FA-F1RB	Fuse Roll Bndg, W4FA
		22	95.32	W6VB	Wing 6th Vert Bndg
		23	98.93	MPF3P	MPF3 Pitch
		24	99.65	MPF3P-F1RB	MPF3 Pitch, Fuse Roll Bndg

Source: D. Ortega, Boeing, *AWT04 Modal Correlated FEM Review*

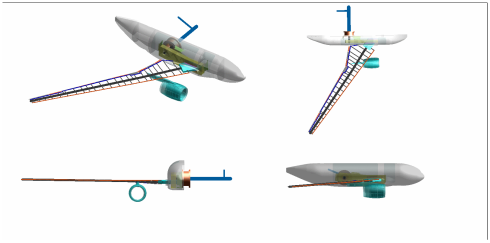
FEM Normal Modes Comparison

Shims-off configuration, first fore-aft bending

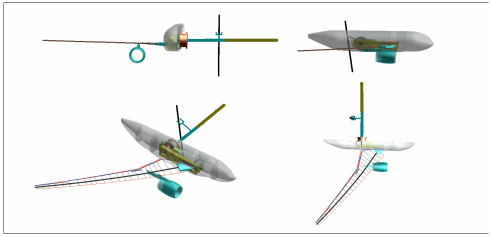
AWT03, 7.730 Hz



AWT04, 8.276 Hz

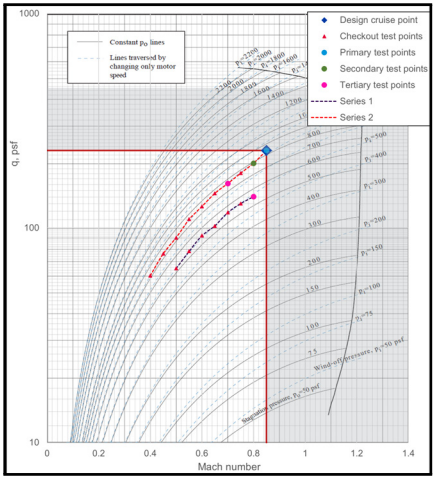


AWT05, 8.059 Hz (7.89 Hz test)



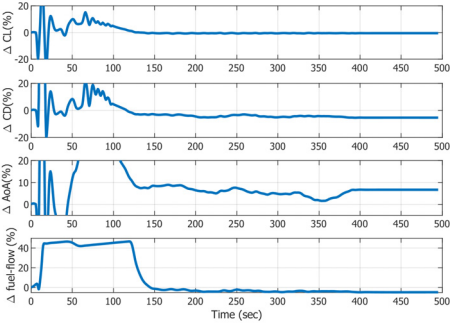
Source: D. Ortega, Boeing, *AWT03 ASE State-Space Modeling*, *AWT04 Modal Correlated FEM Review*, and *AWT05 GVT2 in TDT Modal Correlation FEM Review*

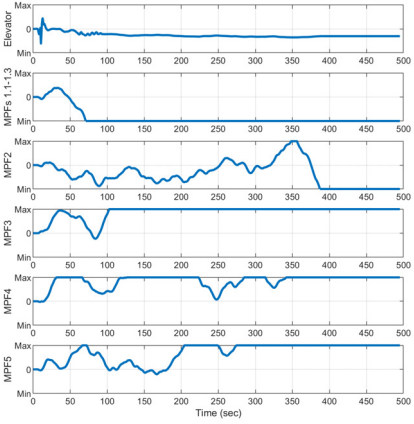
Planned Wind-tunnel Test Conditions



Simulated Full-Scale Fuel Burn Minimization Controller

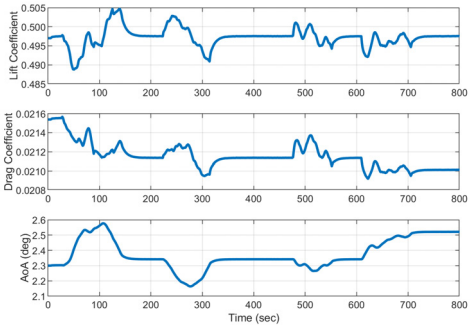
- $M_\infty = 0.85,\ q_\infty = 230$ psf

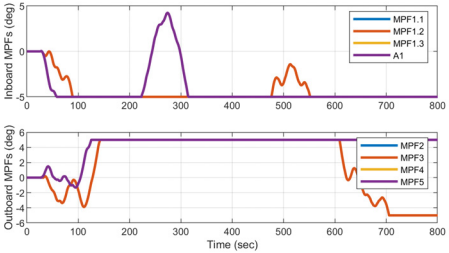




Simulated Model-Scale Drag Minimization Controller

- $M_\infty = 0.85,\ q_\infty = 230$ psf for shims-off configuration





Simulated Model-Scale Gust Load Alleviation Controller

- $M_\infty = 0.70,\ q_\infty = 190$ psf for shims-on configuration