SFTE 2015 Symposium

Aeroelastic Airworthiness Assessment of The Adaptive Compliant Trailing Edge Flaps

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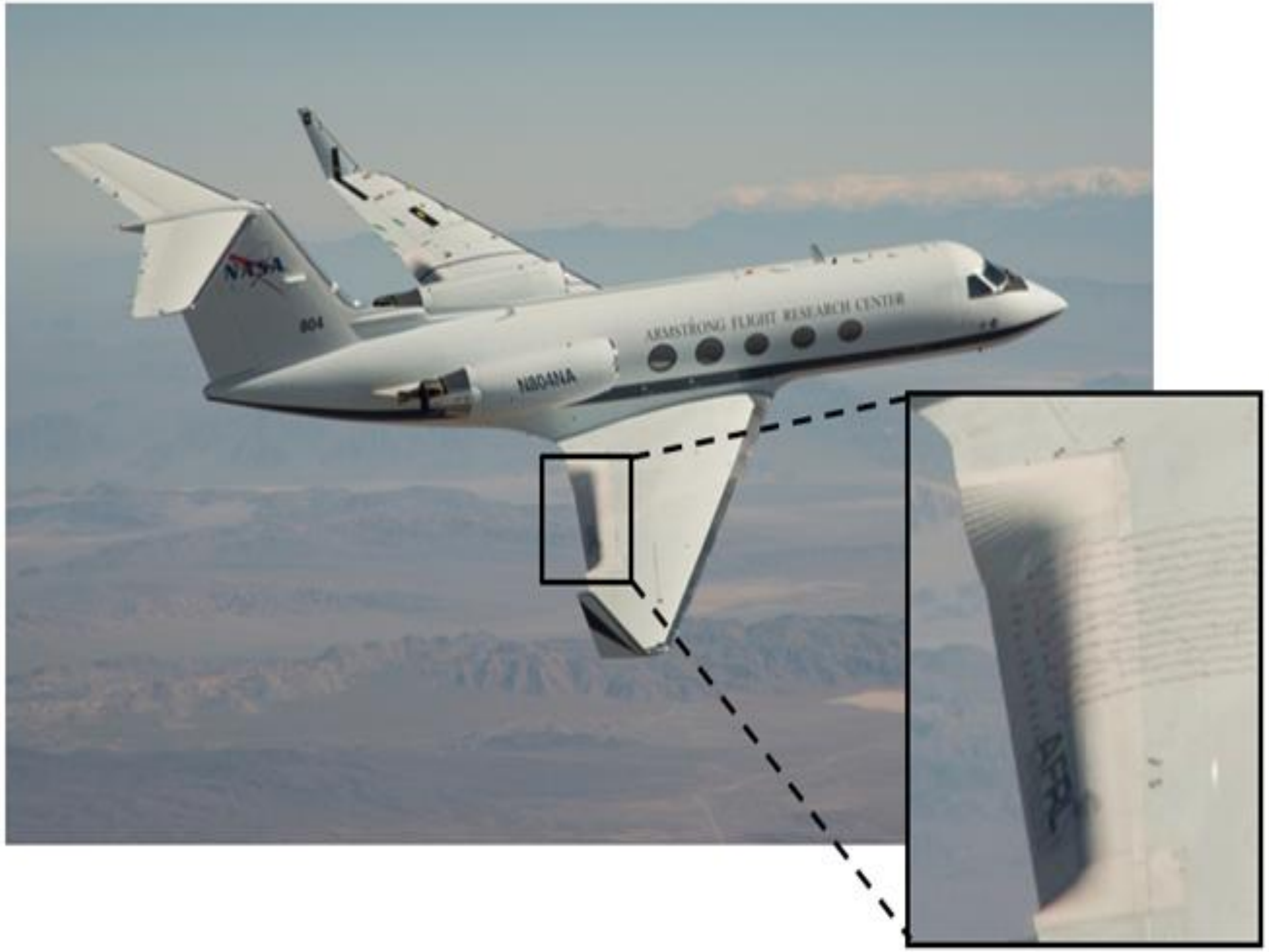
Outline

- Introduction
- Test Article Overview
- NASA AFRC Airworthiness Process
- Ground Testing Approach
- Aeroelastic Analysis
- Flight Testing Approach
- Summary and Conclusions

Introduction

- Small Business Innovation Research program initiative between AFRL and FlexSys, Inc.
- Several aerodynamic benefits of an adaptive airfoil.
  - Less drag
  - Less noise
  - Load distribution capability
- In 2009, AFRL and NASA ERA Program partnered to integrate the Adaptive Compliant Trailing Edge (ACTE) Flaps and NASA Armstrong's SCRAT GIII.
- The ACTE Flaps were designed to deflect from -2° to 30° in flight, shown in the figure.
- NASA AFRC was accountable for systems integration, flight-test execution, and assessing the airworthiness of the integrated flight system.

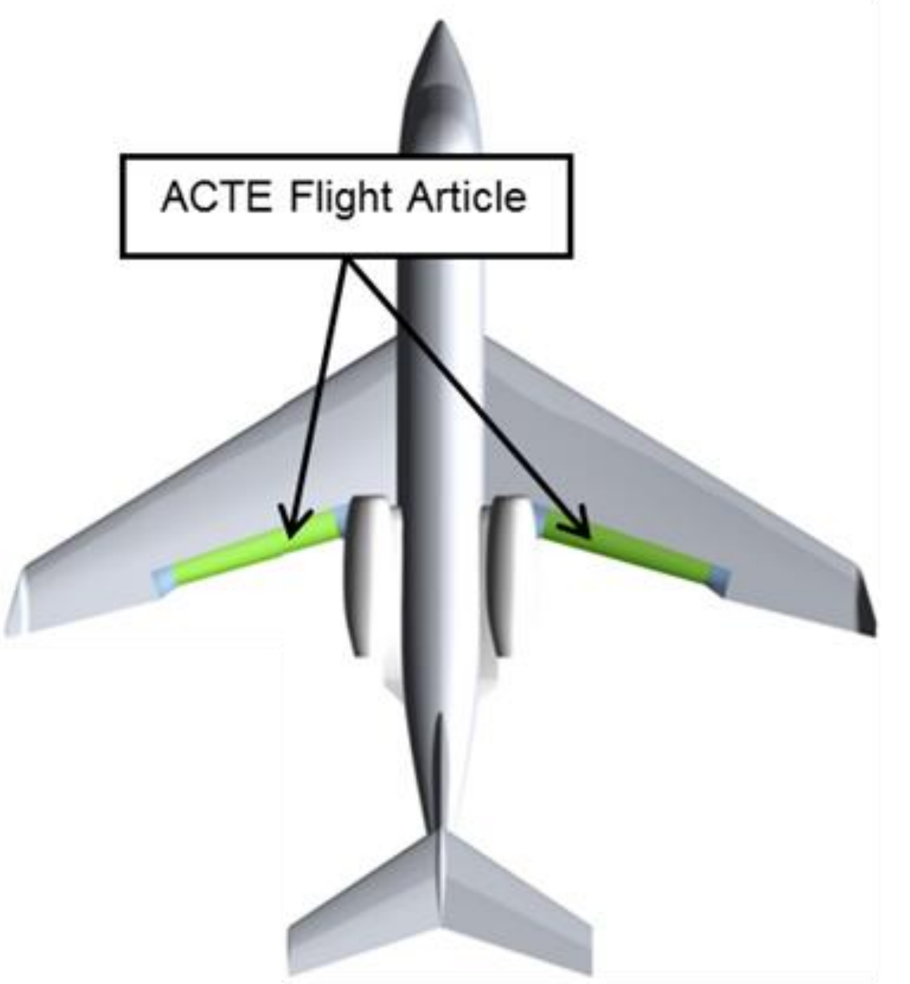


The ACTE flaps at 30° of deflection flown on SCRAT

Test Article Overview

Overview of SCRAT, Flight Testbed

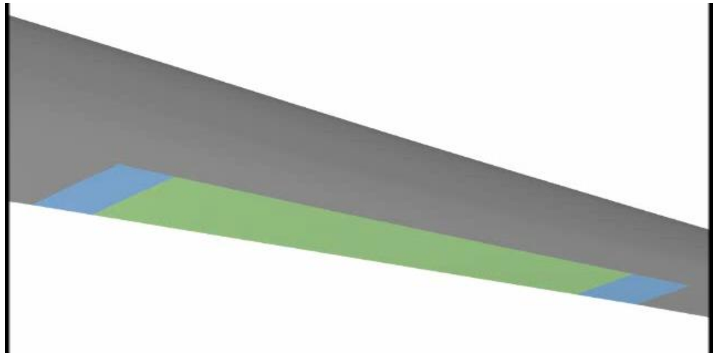
- The SubsoniC Research Aircraft Testbed (SCRAT) is a GIII aircraft modified by NASA AFRC to support flight research experiments intended for advancing flight technologies.
- Instrumentation systems enable acquisition of research data, and a telemetry system transmits the data to the control room, where researchers and engineers monitor research experiments and safety-related information.
- Baseline SCRAT flight characteristics were evaluated and established in the summer of 2012.
- The Fowler flaps, ground and flight spoilers, and all associated hardware were removed from the SCRAT in support of integration of the ACTE flaps.

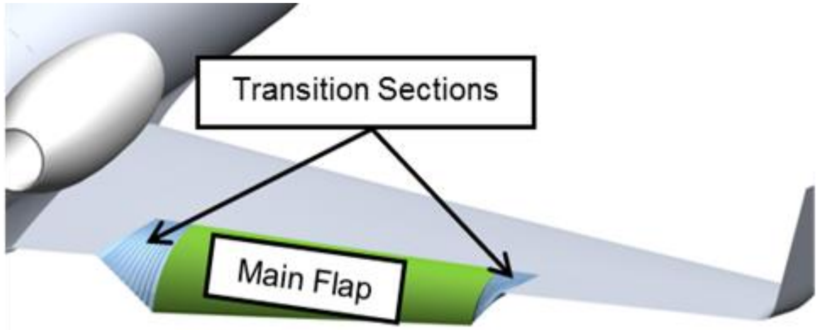


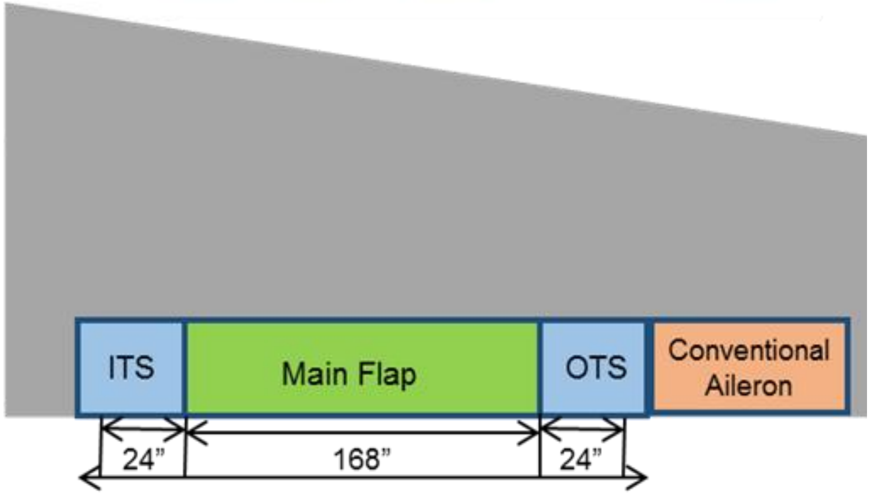
Test Article Overview

Overview of the ACTE Flap, Flight Test Article

- Replaced the NASA SCRAT conventional Fowler flaps on both the left and right sides of aircraft.
- Employed the same attachment points on the wing as the Fowler flaps.
- Each flap measures approximately 19 ft by 2 ft and entirely replaces the Fowler flaps.
- Five main components: 1) inboard transition section (ITS), 2) Main flap, 3) outboard transition section (OTS), 4) the flap spar, 5) the actuation system.
- Flaps deflected before each flight.
- Actuation system deflected ACTE flaps through operational range of -2° (up) to +30° (down), relative to the wing OML.

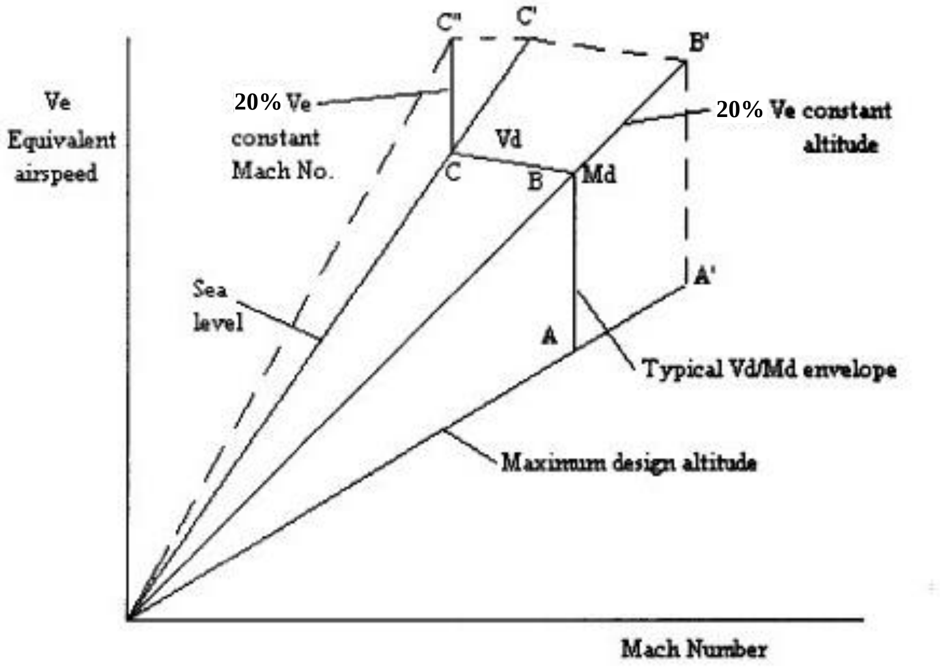


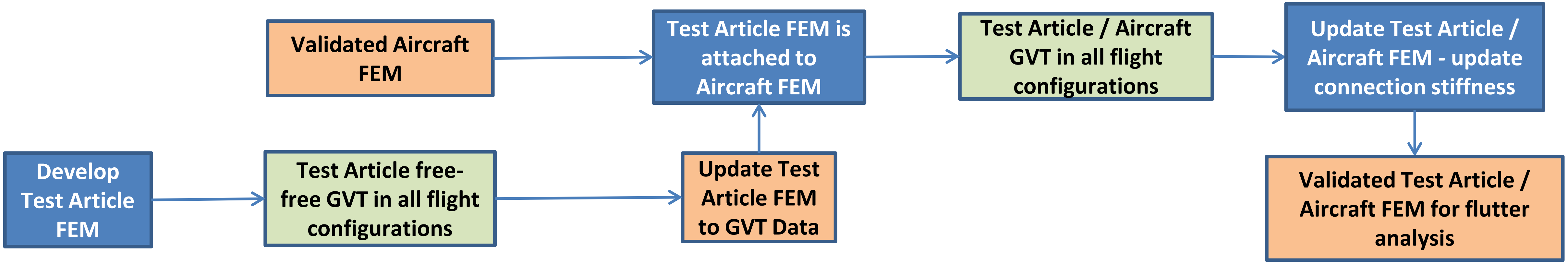




NASA AFRC Aeroelastic Airworthiness

- Evaluation of integrating the ACTE flight article onto the flight testbed aircraft.
- Requirement for 20% flutter margin above ACTE flight envelope.
  - Based on Dryden Handbook requirements at the time of project formulation.
- The large deformations of the ACTE flaps required non-linear analytical methods.
- Analysis and ground testing of prototypes allowed for the development of a process for analyzing and verifying the flight test article.
- Accelerometers installed on the flaps acquired data to capture the in-flight aeroelastic response.

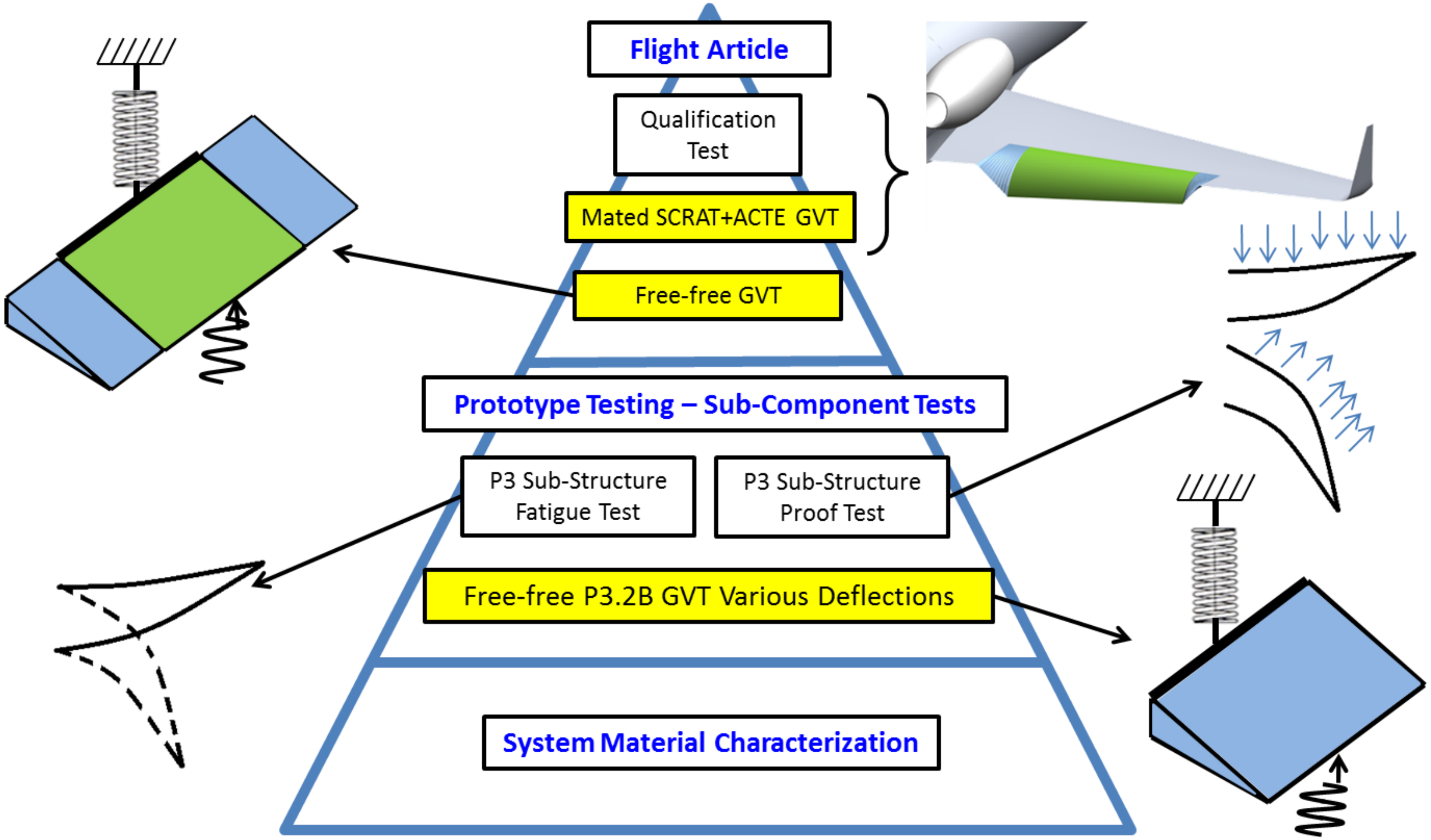




Ground Testing Approach

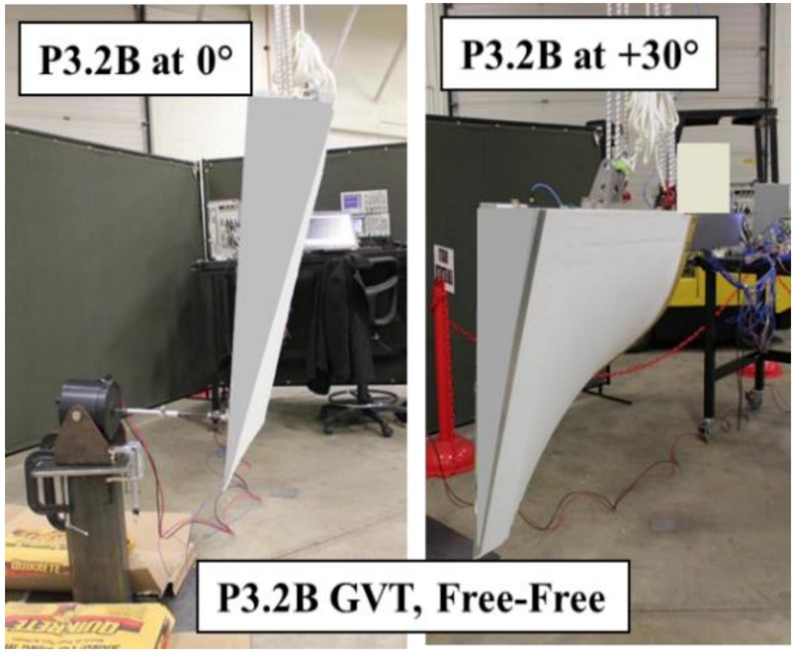
Build-up Approach

- Model validation in the form of ground testing was a requirement in airworthiness.
- Access to prototype structures provided opportunities to develop model validation and ground testing methods for these compliant structures.
- Confidence in modeling and testing methods was first established with prototypes then expanded to full scale flight article.
- Yellow highlights indicate ground vibration tests.



Prototype Ground Vibration Testing

- The Prototype denoted as P3.2B was a full-scale, right-side ITS.
- Objective was to measure modal characteristics at -2°, 0°, and +30°.
- High damping levels were observed.
- Frequencies decreased as a function of increased deflection.
- Unpredicted mode was observed at 30 degs due to lack of stiffness caused by missing main flap section.

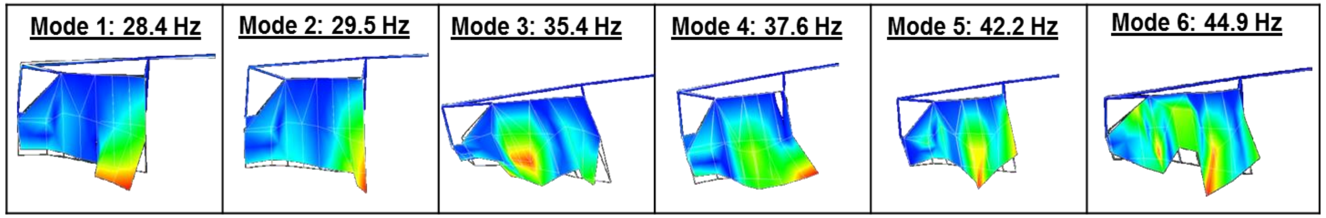


Comparison to Pre-Model Update Frequencies

GVT vs. Analytical FEM

Mode	Frequency, Hz								
	-2° Up			0°			+30° Down		
	Test (Hz)	FEM (Hz)	% Change	Test (Hz)	FEM (Hz)	% Change	Test (Hz)	FEM (Hz)	% Change
1	31.4	27.2	-13%	31.0	26.7	-14%	28.4	29.6	4%
2	---	---	---	---	---	---	29.5	---	---
3	38.2	33.5	-12%	37.	33.0	-11%	35.4	31.7	-11%
4	42.2	39.3	-7%	42.0	38.7	-8%	37.6	37.3	-1%
5	46.3	45.0	-3%	46.2	44.4	-4%	42.2	44.5	5%
6	50.3	46.4	-8%	50.3	46.6	-7%	44.9	45.3	1%

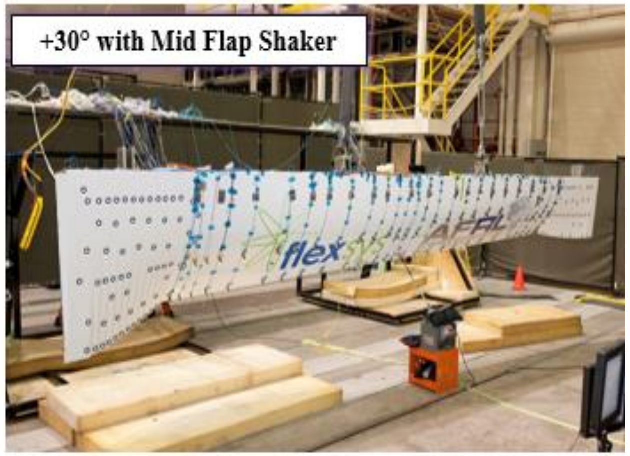
P3.2B GVT Frequencies for 30° Deflection



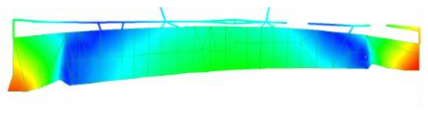
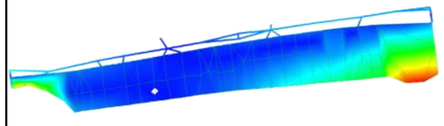
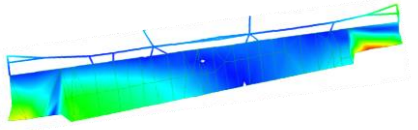
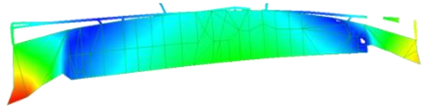
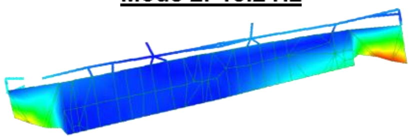
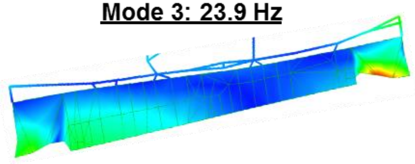
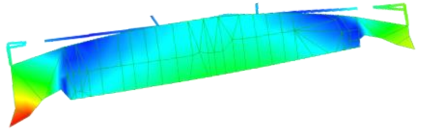
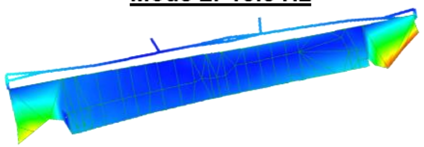
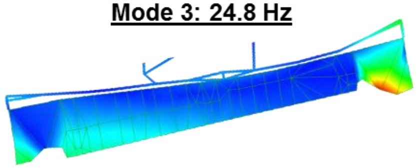
Ground Testing Approach

Flight Article Right Flap Free-Free Ground Vibration Testing

- Test article was right side ACTE flap
- Objectives were to measure modal characteristics at 0°, +15° and +30° with a free-free boundary condition.



Flight Article GVT Frequencies

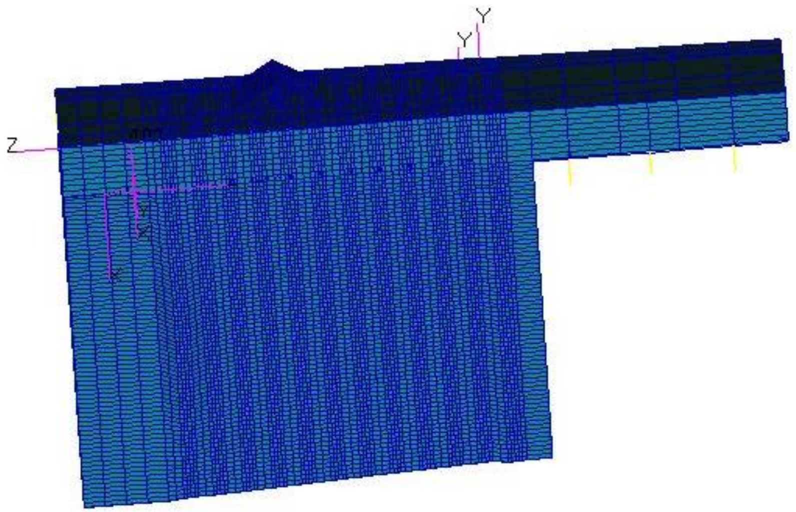
0 degs	Mode 1: 13.4 Hz 	Mode 2: 17.7 Hz 	Mode 3: 22.9 Hz 
15 degs	Mode 1: 14.1 Hz 	Mode 2: 18.2 Hz 	Mode 3: 23.9 Hz 
30 degs	Mode 1: 14.8 Hz 	Mode 2: 18.8 Hz 	Mode 3: 24.8 Hz 

Aeroelastic Analysis

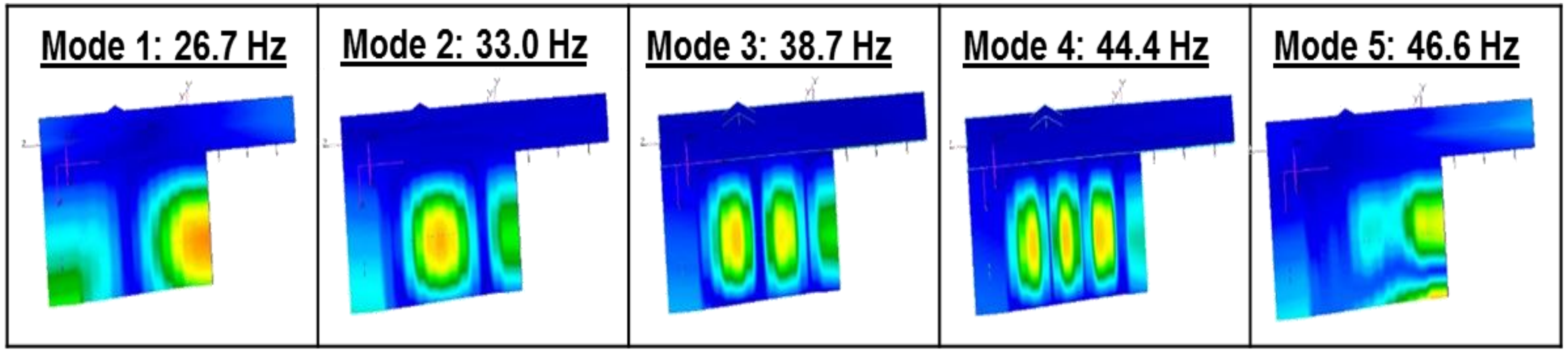
Prototype Model Correlation

- P3.2B finite element model (FEM) was extracted from the full ACTE flap FEM.
- General decrease in frequencies as a function of increasing deflection.
- Analytical method of deflection was established: Ansys vs. Nastran.
- Model update parameters for transition sections were established.

P3.2B 0° FEM for GVT



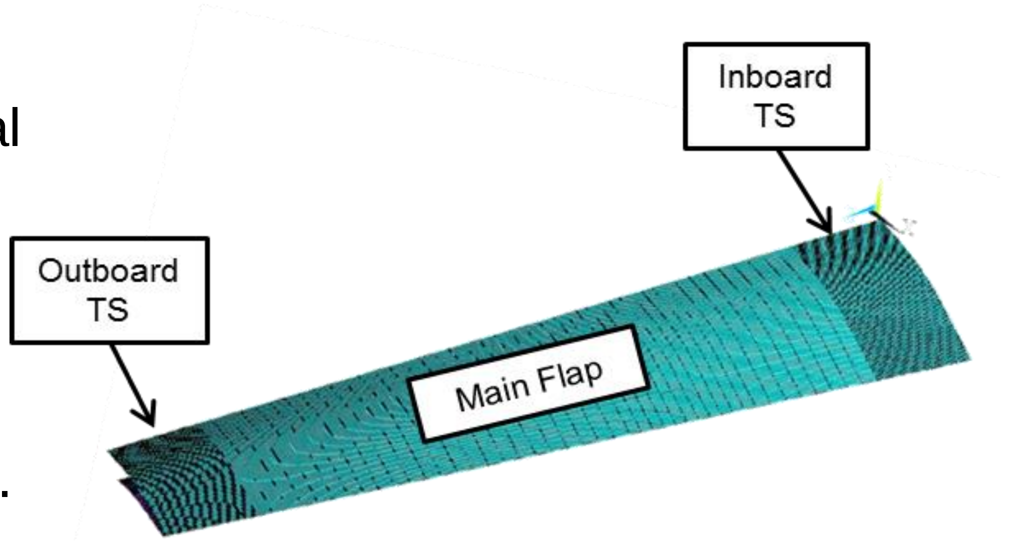
P3.2B 0° FEM Frequencies



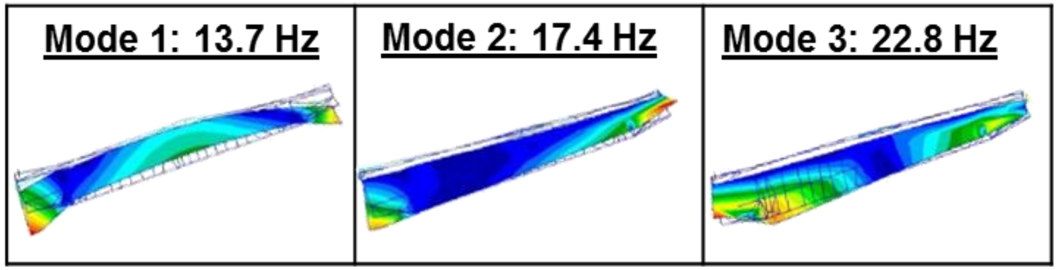
Aeroelastic Analysis

Flight Article Model Update

- Large deformations required non-linear analytical methods.
- Integration into SCRAT FEM required linearization of material properties.
  - An individual FEM was developed for each deflection.
- Nastran FEM produced analytical mode shapes and frequencies.
- General increase in frequencies versus increasing deflection.
- Model update requirements were met.
  - Model update was done using GVT data.



Flight Article 0° Deflection FEM Modes



Flight Article FEM Update Results

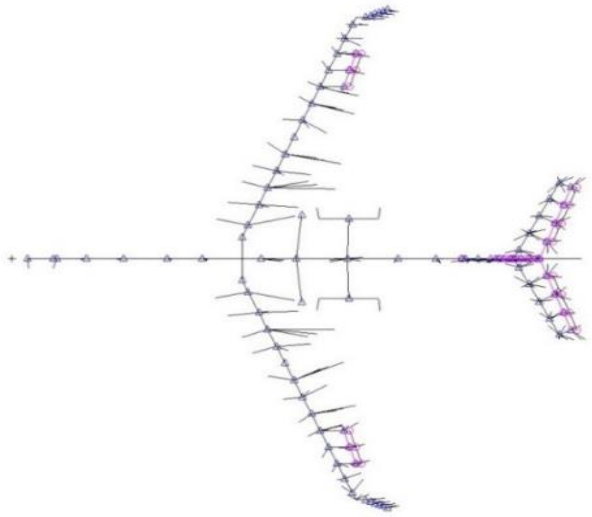
Mode	0° (Wing OML)			15° (Down)			30° (Down)		
	FEM (Hz)	GVT (Hz)	Delta	FEM (Hz)	GVT (Hz)	Delta	FEM (Hz)	GVT (Hz)	Delta
1	13.7	13.4	-2.2%	14.1	14.1	0.0%	14.9	14.8	-0.7%
2	17.4	17.7	1.7%	18.5	18.3	-1.1%	19.2	18.8	-2.1%
3	22.8	22.9	0.4%	23.8	23.9	0.4%	23.8	24.9	4.6%

Aeroelastic Analysis

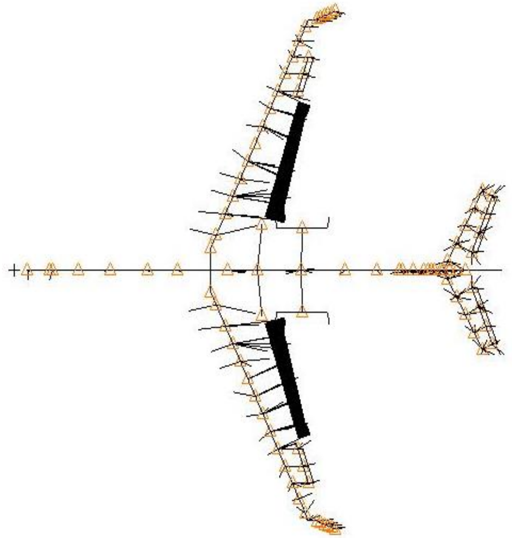
Structural Model Analysis

- SCRAT FEM was previously updated using baseline aircraft GVT data.
- SCRAT was modeled as simple stick model.
- Fowler flaps were modeled as point masses.
  - Removed for integration of ACTE.
  - ACTE flaps used same aircraft attachment locations as Fowler flaps.
  - Attachments modeled as spring elements.
- Model integration and analysis performed using Nastran.
- Flutter results for integrated configuration showed very large margins and removed requirement for mated SCRAT + ACTE GVT.

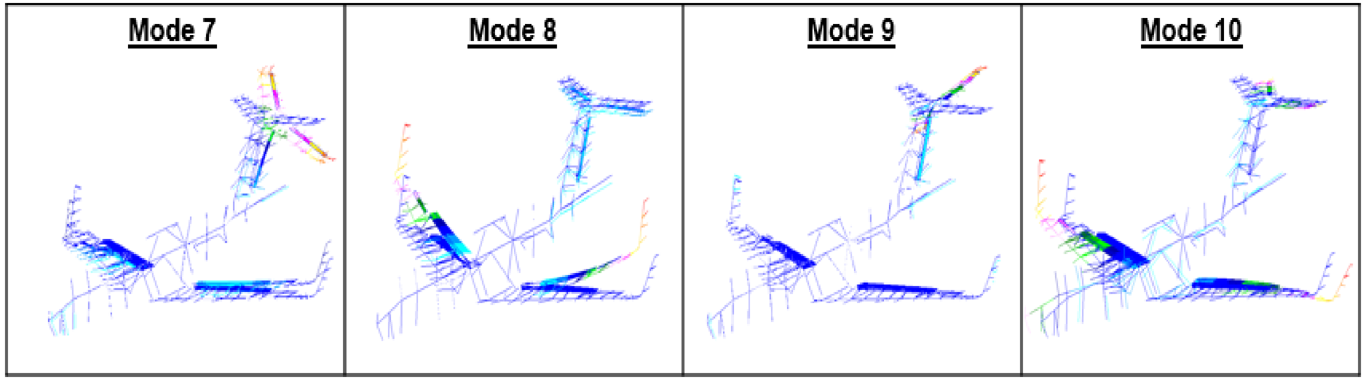
Baseline SCRAT FEM



SCRAT with ACTE flaps



SCRAT FEM modes with ACTE flaps

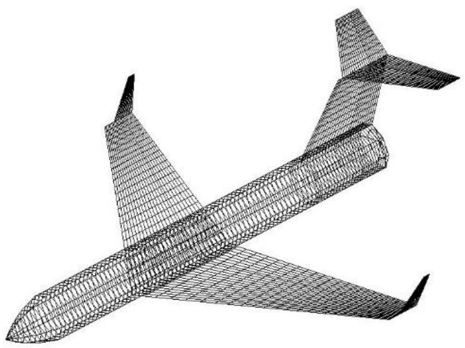


Aeroelastic Analysis

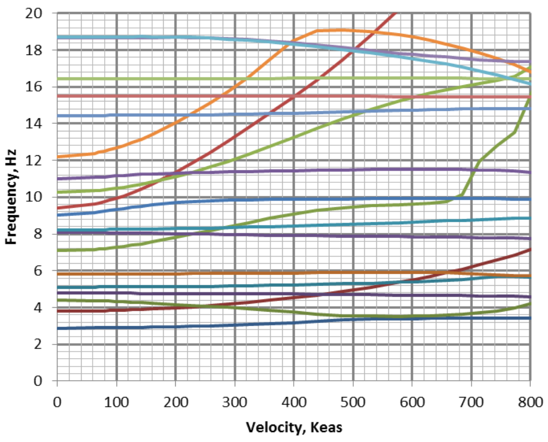
Flutter Analysis

- Flutter analyses were performed using the ZAero code.
  - Matched point analysis
  - Mach numbers 0.6, 0.7, and 0.8
- Flutter analysis encompassed full fuel and empty fuel conditions with the ACTE flaps at various deflections.
- High flutter margins resulted from analysis.
  - Sensitivity analysis was also done with varying spring connection stiffness values.
- Flutter crossing is considered to occur at 2.0% damping.

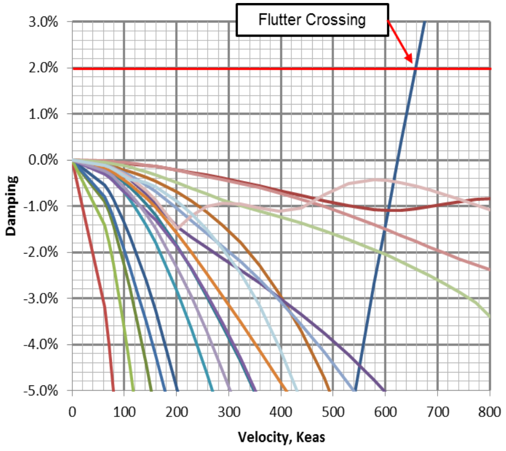
Baseline SCRAT Aero Model



V-f Plot



V-g Plot



SCRAT+ACTE Flutter Results

Flap Angle (deg)	Mach = 0.6			Mach = 0.7			Mach = 0.8		
	Speed (KEAS)	Frequency (Hz)	Altitude (ft)	Speed (KEAS)	Frequency (Hz)	Altitude (ft)	Speed (KEAS)	Frequency (Hz)	Altitude (ft)
30	739	10.3	-38000	690	3.4	-24000	640	3.4	-11200
0	680	10.9	-33200	660	3.4	-21900	615	3.4	-8430
-2	680	9.5	-33400	650	8.7	-20000	640	2.9	-11500

Flap Angle (deg)	Mach = 0.6			Mach = 0.7			Mach = 0.8		
	Speed (KEAS)	Frequency (Hz)	Altitude (ft)	Speed (KEAS)	Frequency (Hz)	Altitude (ft)	Speed (KEAS)	Frequency (Hz)	Altitude (ft)
30	-	-	-	800	3.4	-24000	740	5.7	-23200
0	700	3.4	-35000	640	3.3	-19200	580	3.3	-5470
-2	-	-	-	735	7.4	-27700	690	7.2	-15500

Flight Testing Approach

Pre-flight Frequency Predictions

- Pre-flight predictions compared against flight testing results to validate aeroelastic model.
- 0°, 15°, and 30° were considered anchor points for model validation.
  - Modes for anchor analyses configurations were tracked as a function of dynamic pressure.
- The in-between deflections were used for spot-checking trends between anchor points.
- A set of pre-flight predictions was developed for each flap deflection analyzed for both empty fuel and full fuel conditions.
  - Includes both critical flutter mechanisms as well as ACTE modes.

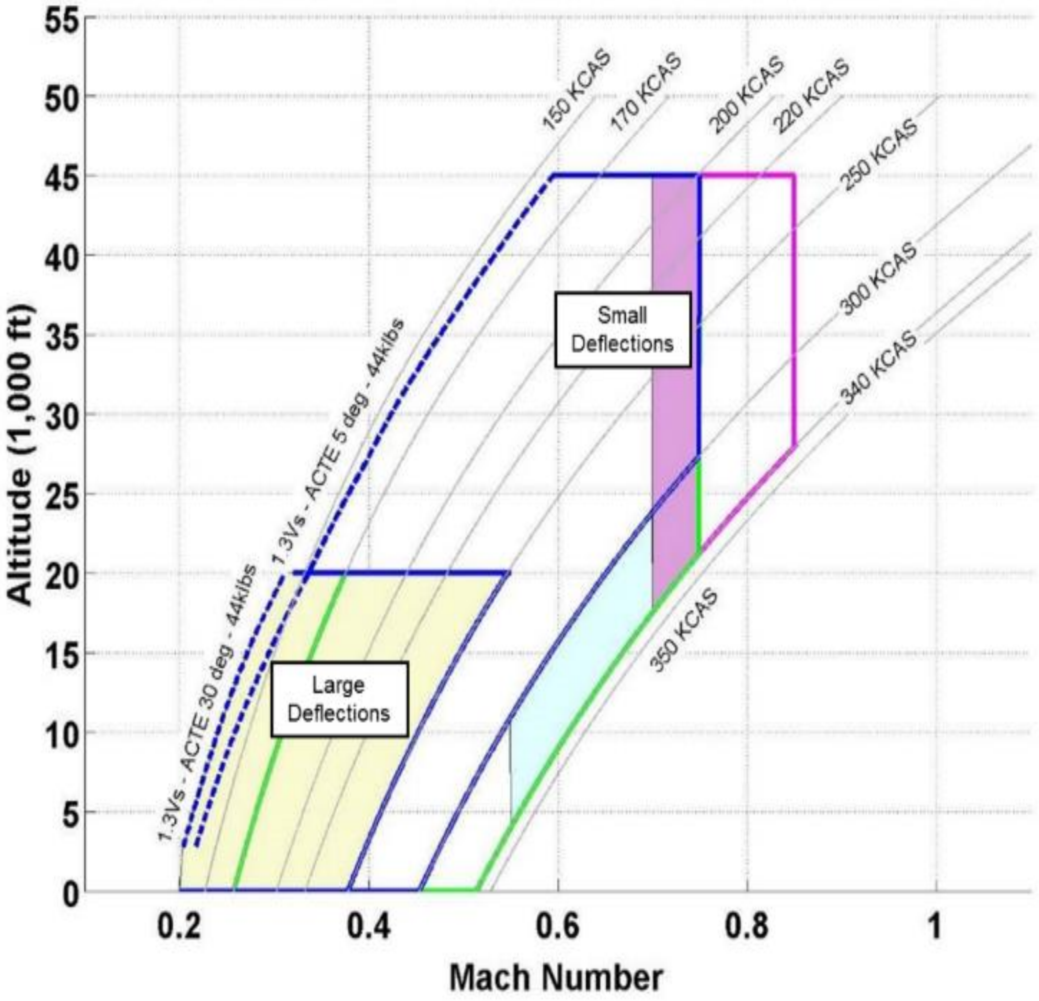
SCRAT with ACTE 0° (EMPTY FUEL)		SCRAT with ACTE 0° (FULL FUEL)	
Description	**Freq.**	**Description**	**Freq.**
Vertical Tail Bending	2.87	Vertical Tail Bending	2.61
Wing 1B Symm	3.43	Wing 1B symm	2.54
Wing 2B antisymm	7.87	Wing 2B antisymm	6.34
Fin torsion, Stab 1B antisymm	8.10	Fin torsion, Stab 1B antisymm	7.42
Wing 2B symm, elevator rot symm	8.46	Wing 2B symm	7.04
Wing 3B antisymm, ACTE OTS anti	12.99	Wing 3B antisymm, ACTE ITS anti	12.23
Wing 1T symm, ACTE ITS symm	14.89	Wing 1T symm, ACTE symm/stab symm	11.62
Wing 1T antisymm, ACTE ITS symm	15.43		
		Wing 3B symm, ACTE span bending	13.55
		Wing 3B antisymm, ACTE span bending	14.71
Winglet 1B symm, ACTE ITS symm	15.53	Winglet1B symm, ACTE ITS symm	18.44
Winglet 1B anti, ACTE span bend anti	16.04	Winglet 1B anti, ACTE ITS anti	16.45
Winglet 1B symm, ACTE span bend sym	16.97	Winglet 1B symm, ACTE span bending	15.27
Wing 1T anti, ACTE span bend anti	17.61		
		ACTE ITS symm	17.03
		ACTE OTS symm	17.27
Winglet 1B symm, ACTE ITS symm	19.28	Winglet symm, ACTE OTS	20.05
Winglet 1B anti, ACTE ITS anti	19.34	Winglet antisymm, ACTE OTS	20.23
Winglet 1B anti, ACTE ITS anti, engine pitch	19.91		
Wing 2T anti, ACTE flap rotation anti	21.77	Wing 2T anti, ACTE flap rotation anti	19.09
ACTE rotation anti	23.16		

Flight Testing Approach

Project Approach

- Two flight envelopes
  - Small flap deflections: High/fast and Low/fast
  - Large flap deflections: Low/slow
- Project employed build-up flight testing approach.
  - Strategically increased Mach number and dynamic pressure to reduce risk of encountering a potential aeroelastic instability
  - Low/slow => High/slow =>High/fast => Low/fast
- A comprehensive set of maneuvers, such as raps, 2-1-1's, steady heading side slips, and windup turns were executed at discrete test points throughout the flight envelope.
  - Raps and SHSS provided the excitation necessary to excite both the aircraft and ACTE flap modes of interest.

ACTE Flight Envelope



Flight Testing Approach

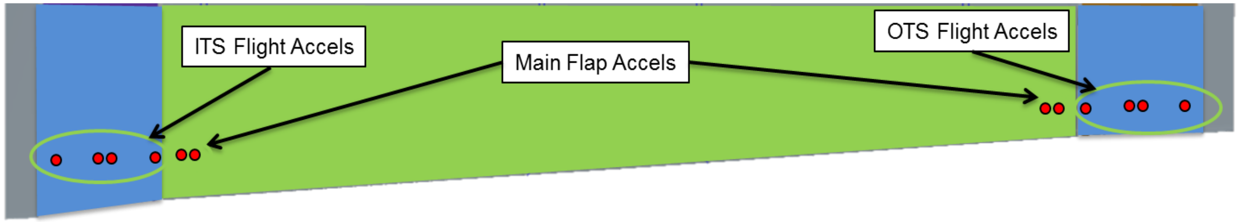
Flight Test Instrumentation

- SCRAT instrumented for baseline flight-testing based on flutter results.
- Each ACTE flap instrumented with accelerometers based on SCRAT+ACTE flutter analyses.

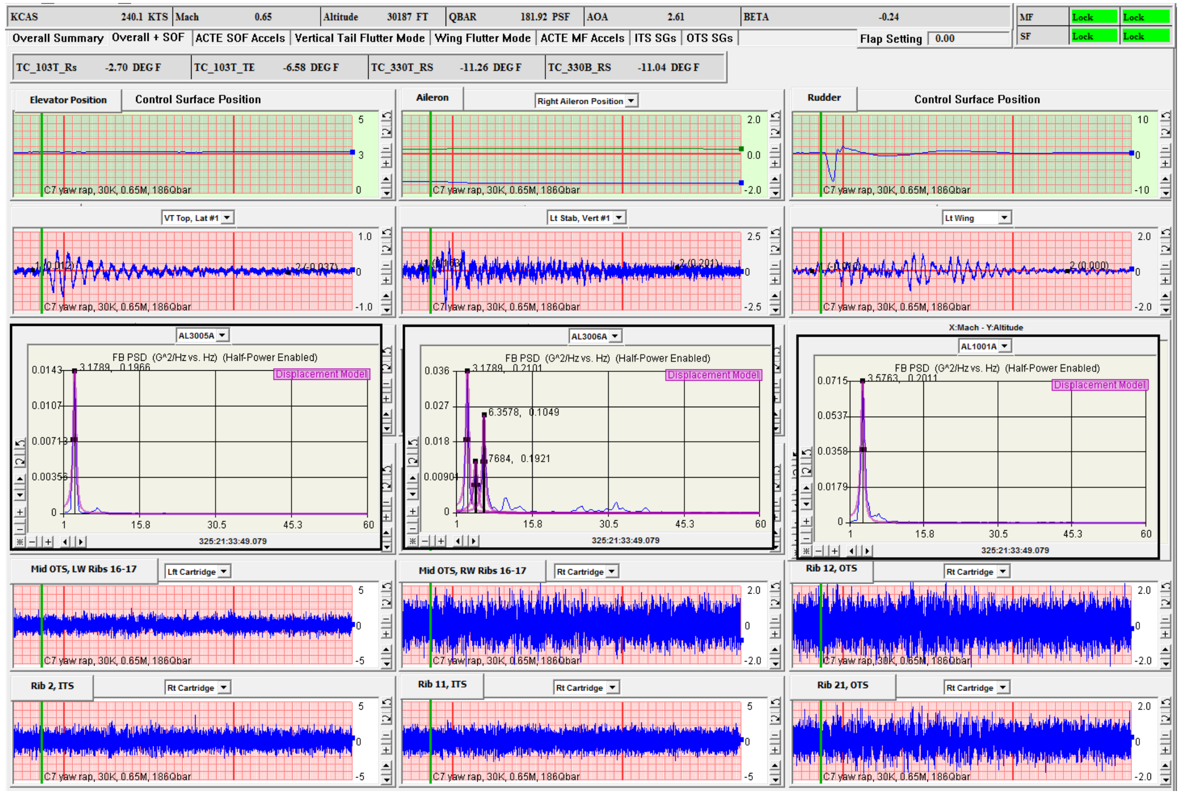
Control Room Operations

- Control surface raps were main excitation for aeroelastic purposes.
- Control room staffed to monitor key flight-testing parameters.
- Displays built with IADS to monitor time histories and calculate power spectral densities (PSDs) to enable the estimation of damping.

ACTE Flight Accelerometers



Control Room Display



Flight Testing Approach

SCRAT and ACTE In-flight Aeroelastic Response

ACTE 0° In-flight ACTE response

Mode Description	Freq. (Hz)	Damping (%)
Vertical tail bending	3.1	16.6
Stab 1B anti	4.3	25.8
Wing 2B antisymm	7.1	13.4
Wing 3B anti, Left ACTE OTS anti	11.1	7.6
Wing 3B anti, Right ACTE OTS anti	12.2	12.1
Wing 3B symm, ACTE span bending	13.2	11.2
Wing 1T antisymm, ACTE ITS symm	15.7	7.3
Winglet 1B symm, ACTE span bend symm	16.2	13.9
Wing 1T anti, ACTE span bend anti	17.8	8.8
Winglet 1B symm, ACTE ITS symm	18.8	4.2
Winglet 1B anti, ACTE ITS anti	19.3	9.8

Comparison to ACTE 0° Analytical Predictions

Mode Description	FEM Empty Fuel (Hz)	Flight Test (Hz)	FEM Full Fuel (Hz)
Vertical tail bending	2.8	3.1	2.6
Stab 1B anti	4.4	4.3	4.3
Wing 2B antisymm	7.8	7.1	6.3
Wing 3B anti, Left ACTE OTS anti	12.9	11.1	10.9
Wing 3B anti, Right ACTE OTS anti	12.9	12.2	10.9
Wing 3B symm, ACTE span bending	--	13.2	13.5
Wing 1T antisymm, ACTE ITS symm	15.4	15.7	--
Winglet 1B symm, ACTE span bend symm	16.9	16.2	15.2
Wing 1T anti, ACTE span bend anti	17.6	17.8	--
Winglet 1B symm, ACTE ITS symm	19.2	18.8	--
Winglet 1b anti, ACTE ITS anti	19.3	19.3	16.4

Summary and Conclusions

- As part of NASA's ERA program, a partnership with the AFRL and FlexSys, Inc. was created to demonstrate two full-scale lifting surfaces that enable a continuous mold line.
- Integrating the SCRAT and ACTE FEMs combined a model requiring non-linear analysis methods into a linear analysis process.
- A build-up testing and modeling approach enabled a path-finding exercise to develop a set of modeling and testing practices to apply to the flight test article.
- Ability to test prototype test articles before flight test article provided experience modeling and validating the compliant structures.
- A combined flutter analysis was performed for a set of ACTE deflections to compare directly against flight testing results. Pre-flight predictions showed the flutter margin requirement was satisfied.
- A flight testing approach was developed using control surface raps and control room displays providing frequency and damping estimates.
- In addition to conventional aeroelastic inputs, in-flight excitation was needed from other sources. Flight test maneuvers for other disciplines served as good excitation sources.
- In-flight frequency results showed good model correlation and good damping values.
- Project is preparing to extend Mach to 0.85.