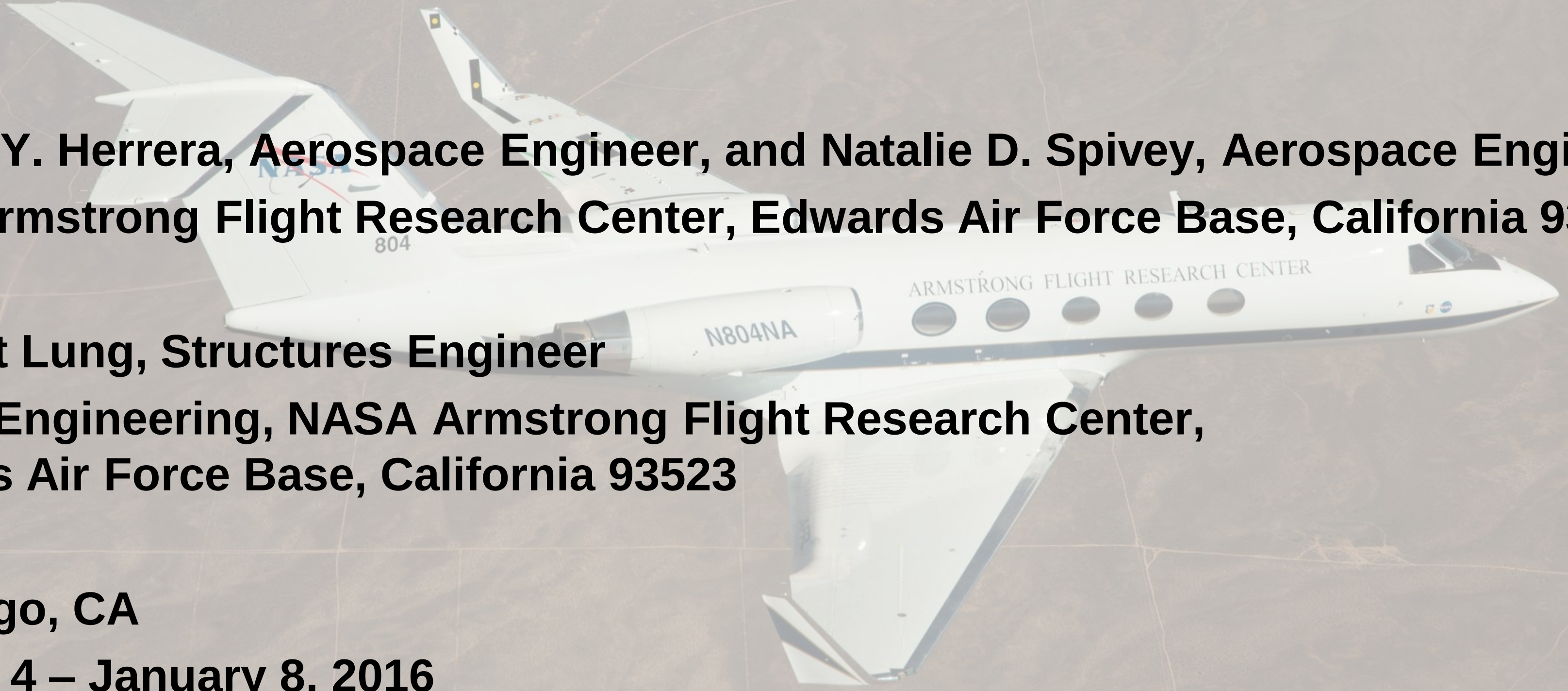
AIAA SciTech 2016 Structures, Structural Dynamics, and Materials Conference

Aeroelastic Response of the Adaptive Compliant Trailing Edge Transition Section



Claudia Y. Herrera, Aerospace Engineer, and Natalie D. Spivey, Aerospace Engineer

NASA Armstrong Flight Research Center, Edwards Air Force Base, California 93523

Shun-fat Lung, Structures Engineer

Jacobs Engineering, NASA Armstrong Flight Research Center,
Edwards Air Force Base, California 93523

San Diego, CA

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Outline

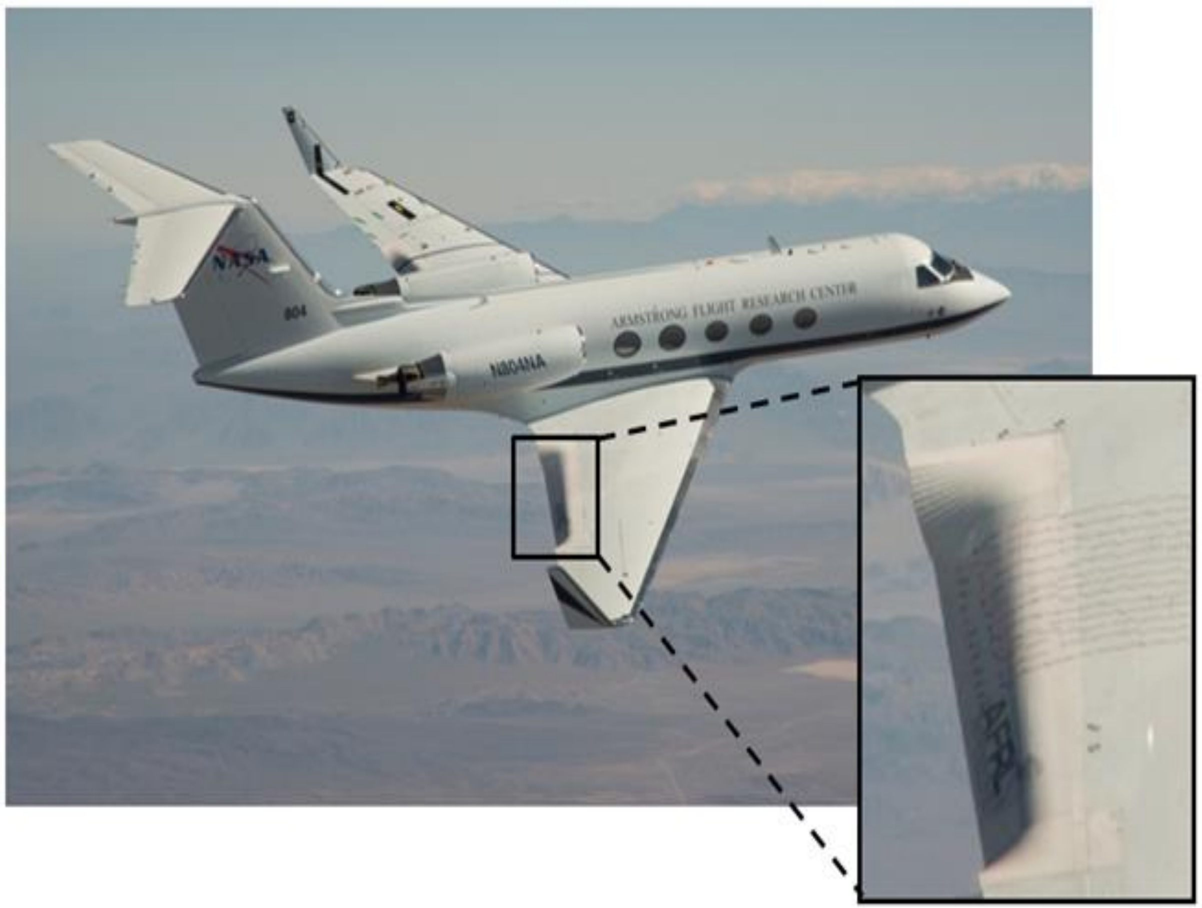
- Introduction
- Test Article Overview
- Ground Testing Approach
- Aeroelastic Analysis
- Flight Testing Approach
- Summary and Conclusions

Introduction

- Small Business Innovation Research program initiative between AFRL and FlexSys, Inc.
- Several aerodynamic benefits of an adaptive airfoil
  - Noise reduction
  - Structural Load alleviation
  - Improve aerodynamic efficiency
  - Increase control surface effectiveness

Next Gen Aircraft

- AFRL/NASA ERA partnership to integrate the Adaptive Compliant Trailing Edge (ACTE) Flaps and NASA Armstrong's SCRAT GIII
- Designed to deflect from -2° to 30° in flight**,** shown in the figure
- Accountable for systems integration, flight-test execution, and assessing the airworthiness of the integrated flight system to support a flight test campaign that occurred from November 2014 – April 2015
- Clearance of transition sections and flaps done with AFRC airworthiness processes and requirements

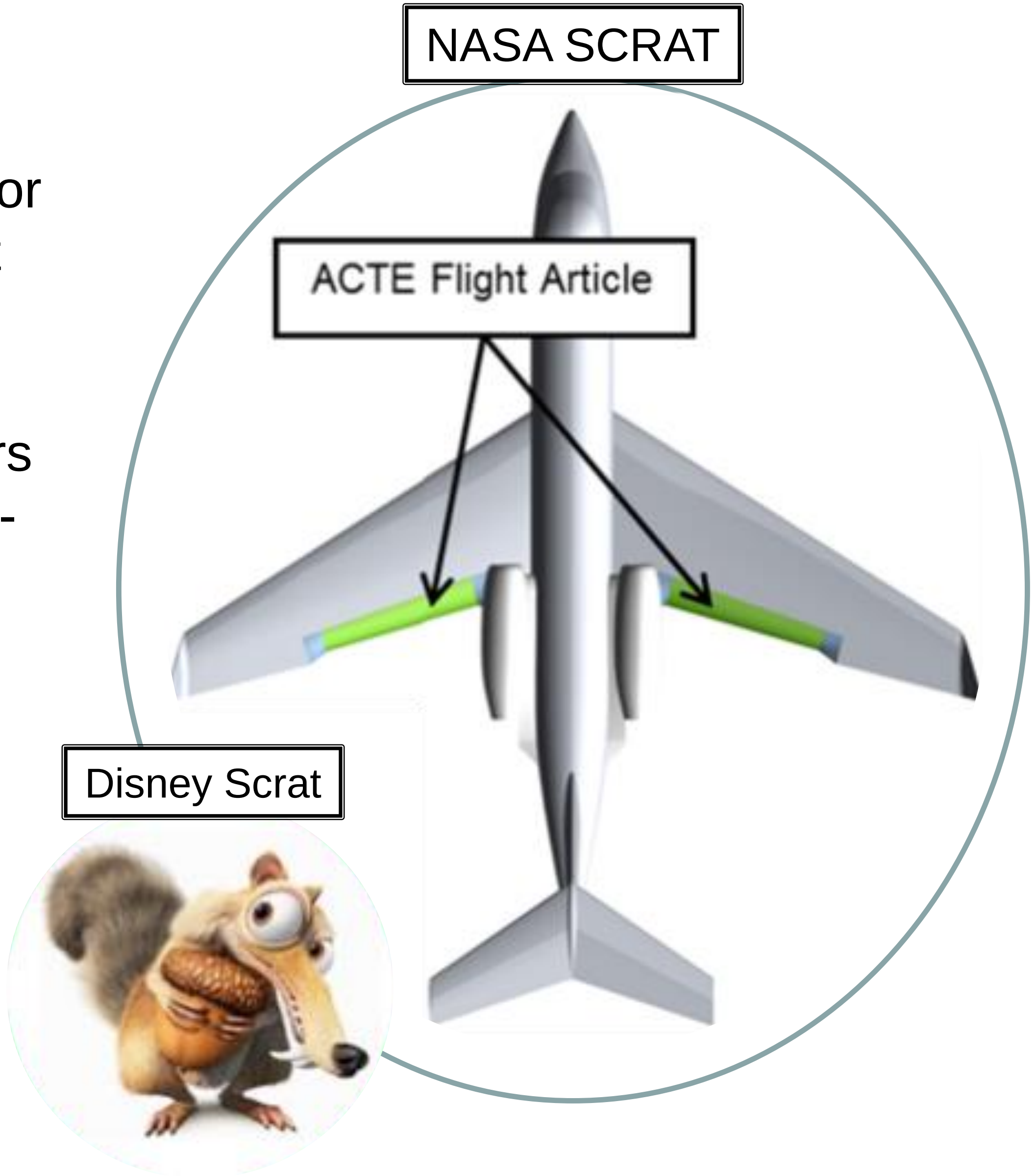


The ACTE flaps at 30° of deflection flown on SCRAT

Test Article Overview

Overview of SCRAT, Flight Testbed

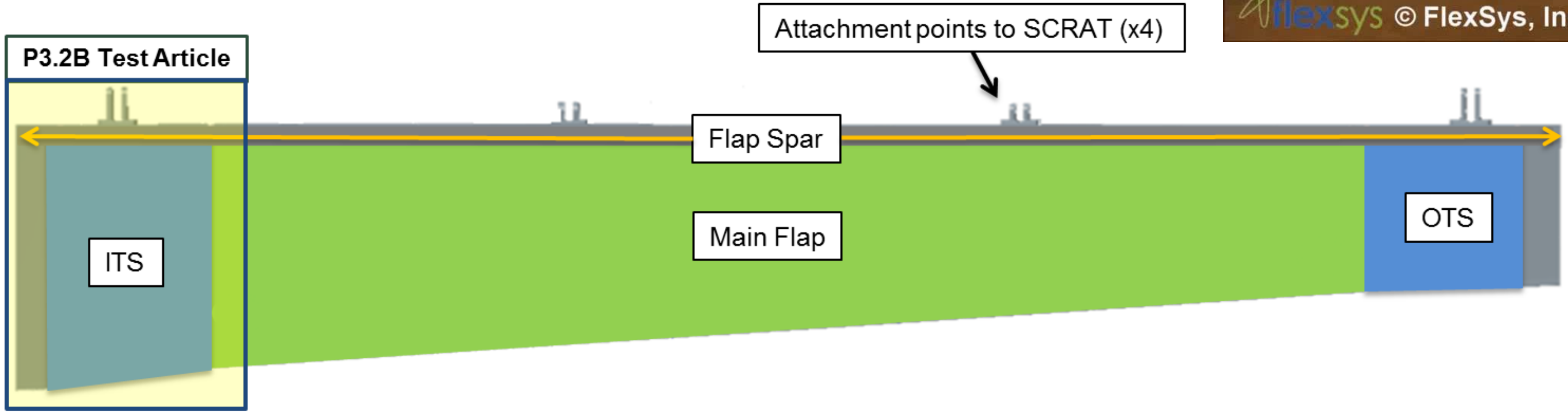
- A modified GIII, SubsoniC Research Aircraft (SCRAT), for flight research experiments intended for advancing flight technologies
- Acquisition of research data, and a telemetry system transmits the data to the control room, where researchers and engineers monitor research experiments and safety-related information
- Baseline SCRAT flight characteristics well understood.
- Flight hardware removed from the SCRAT in support of integration of the ACTE flaps



Test Article Overview

Overview of the ACTE Flap, Flight Test Article

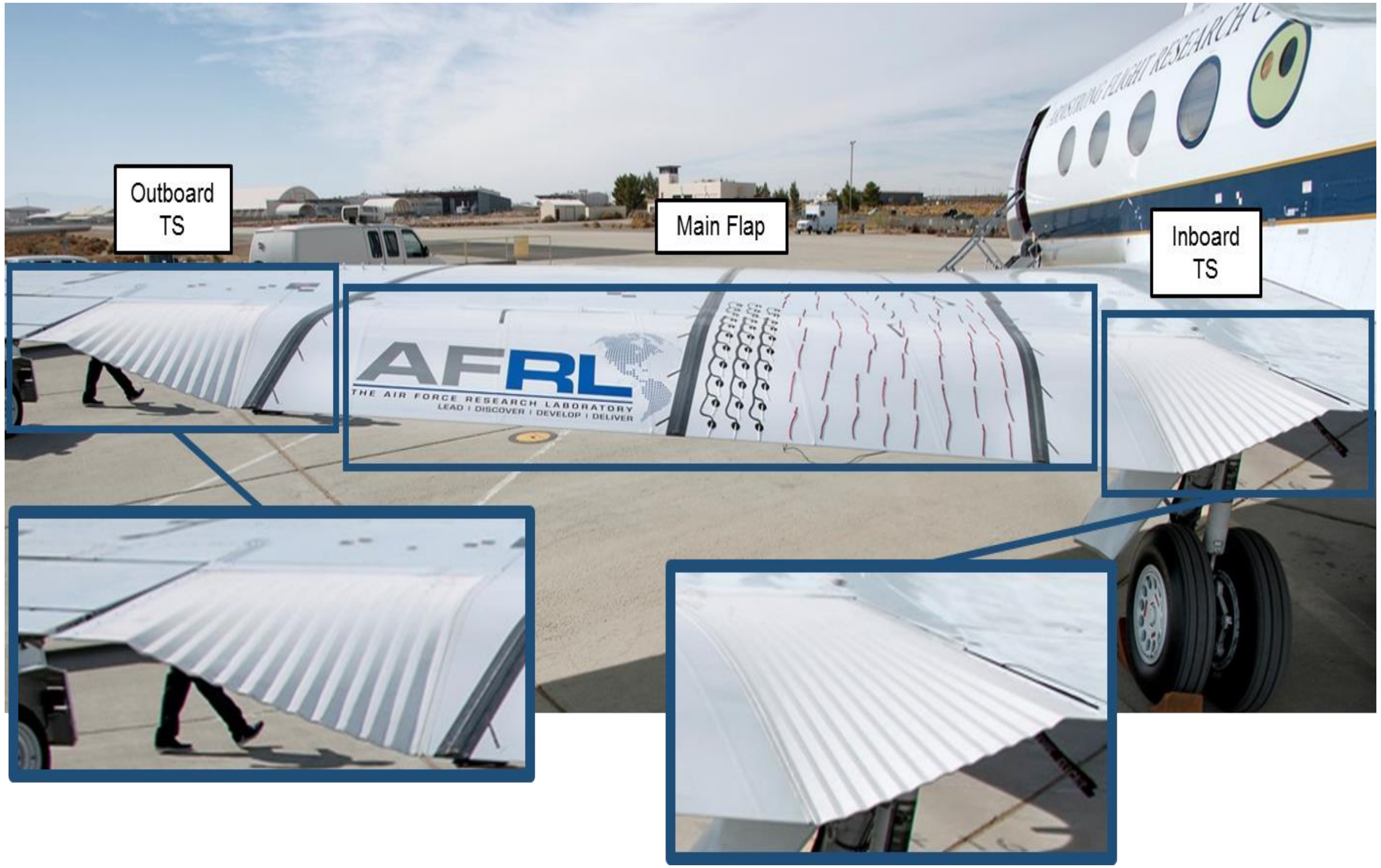
- Replaced the NASA SCRAT conventional Fowler flaps on both the left and right sides of aircraft
- Employed the same attachment points on the wing as the Fowler flaps
- Measures approximately 19 ft by 2 ft and entirely replaces a Fowler flap
- Five main components: 1) inboard transition section (ITS), 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



Test Article Overview

Importance of the Transition Sections

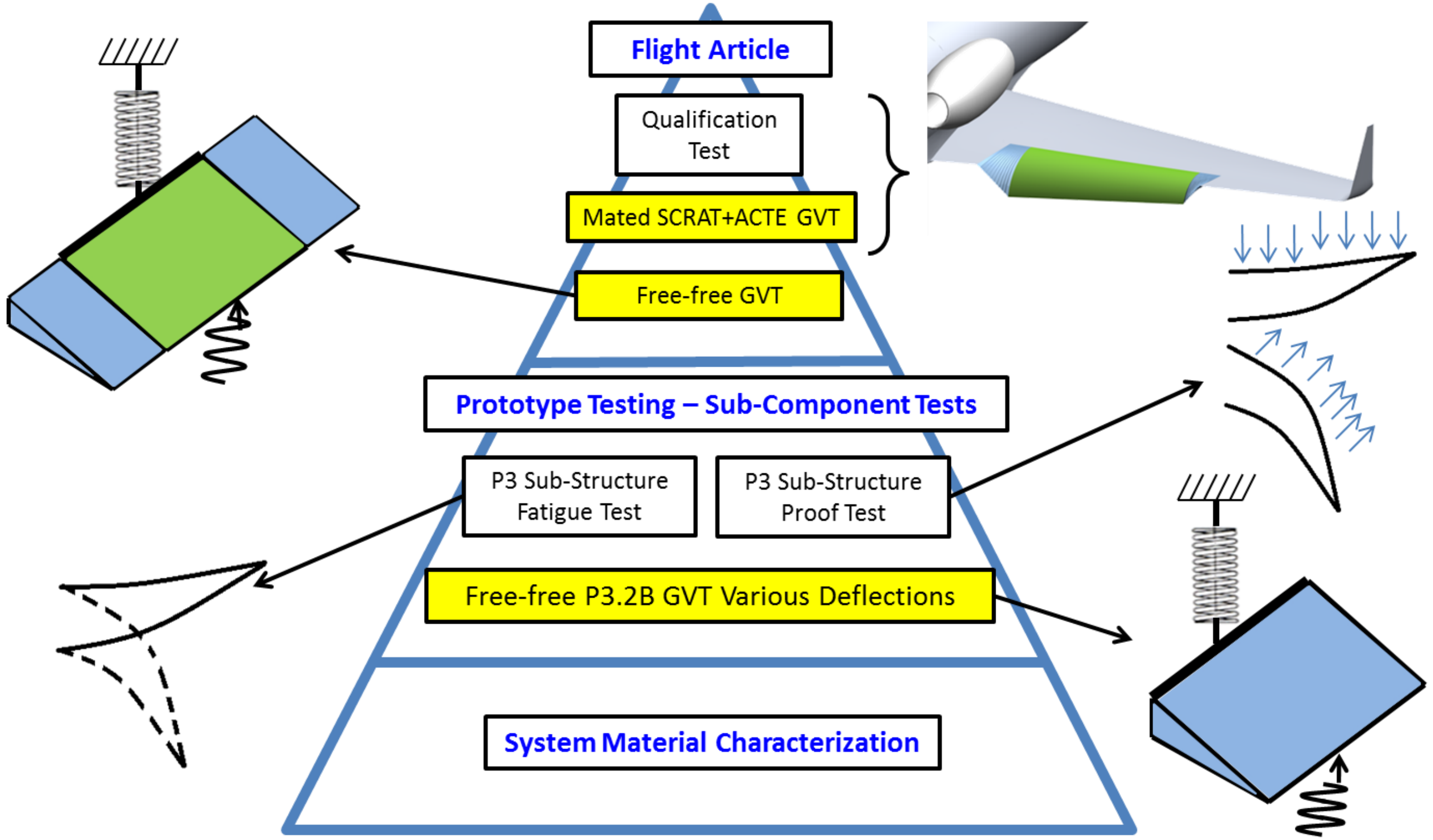
- Created the continuous mold-line as the flap was deflected through its full range of operation
- Connected main flap section to wing OML
- Inboard and Outboard are similar in shape; vary in size by wing taper
- Strong but flexible enough to withstand the aero loads experienced during flight
- Operation exercised flap through large deformations
- Potential for supersonic flow, increasing chance of failure.
- Monitoring of panel-type responses during flight-testing.



Ground Testing Approach

Build-up Approach to Ground Testing

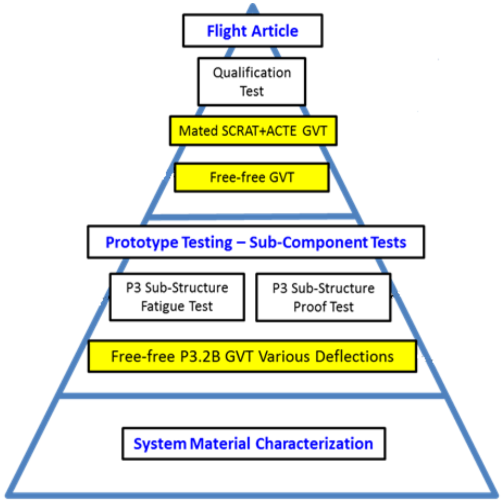
- Model validation in the form of ground testing
- Building of confidence in modeling and testing methods
- Insight into the compliant structure technology early in the project
- Access to prototype test articles
  - Prototype series 2 and 3
  - “A” designation referred to main flap
  - “B” designation referred to TS’s
- Ground vibration tests highlighted yellow

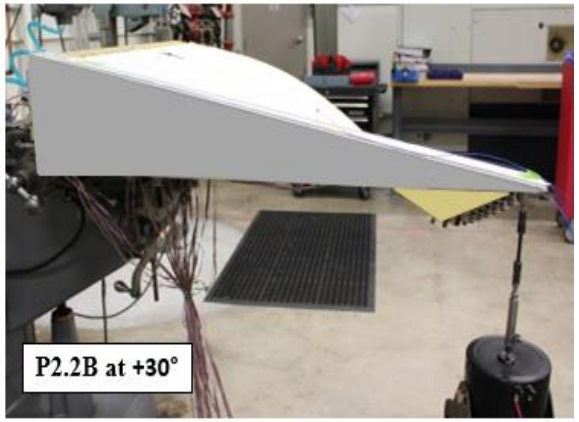


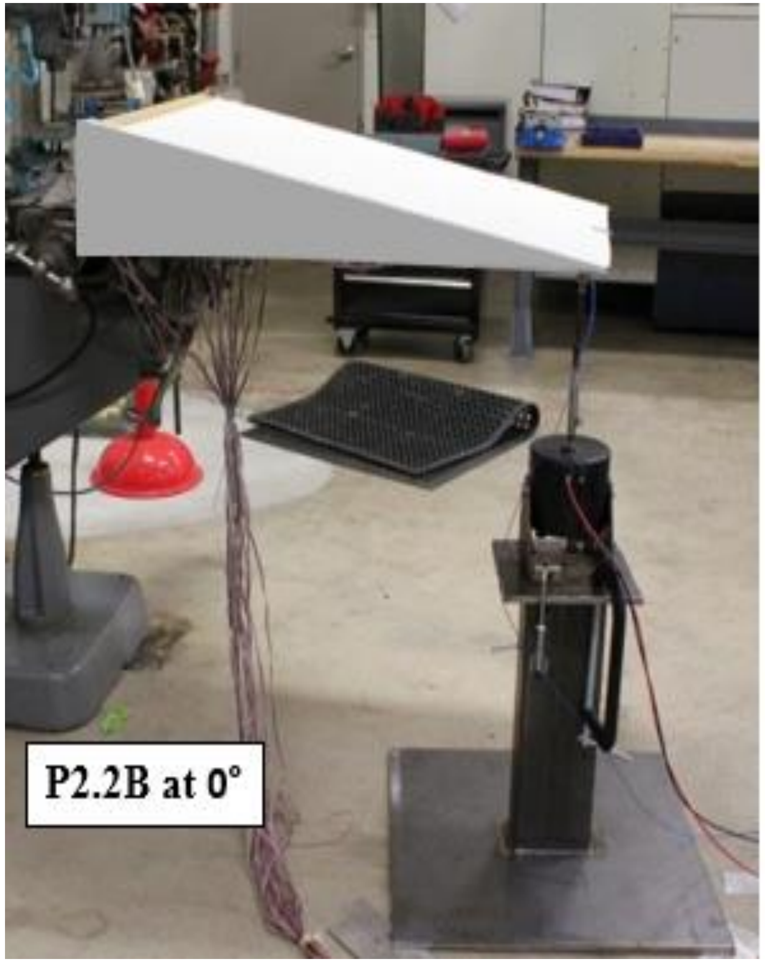
Ground Testing Approach

Prototype - P2.2B Ground Vibration Testing

- The test objectives were:
  1) Consider any apparent change in stiffness due to changing the flap deflection
  2) Evaluate accelerometers as instrumentation on flexible structure
  3) Evaluate various types of excitation methods and instrumentation
  4) Evaluate finite element model (FEM) techniques employed
- Two test configurations
  1) Cantilevered from a milling machine
  2) Free-free using bungees
- Lessons Learned
  1) Local modes on test structures should be instrumented.
  2) Non-structural components should be modeled
  3) Certain accelerometer locations were more capable of capturing mode shapes
  4) Shaker excitation and impact hammer were needed for excitation
  5) Most favorable excitation location was on the fixed wing representative portion



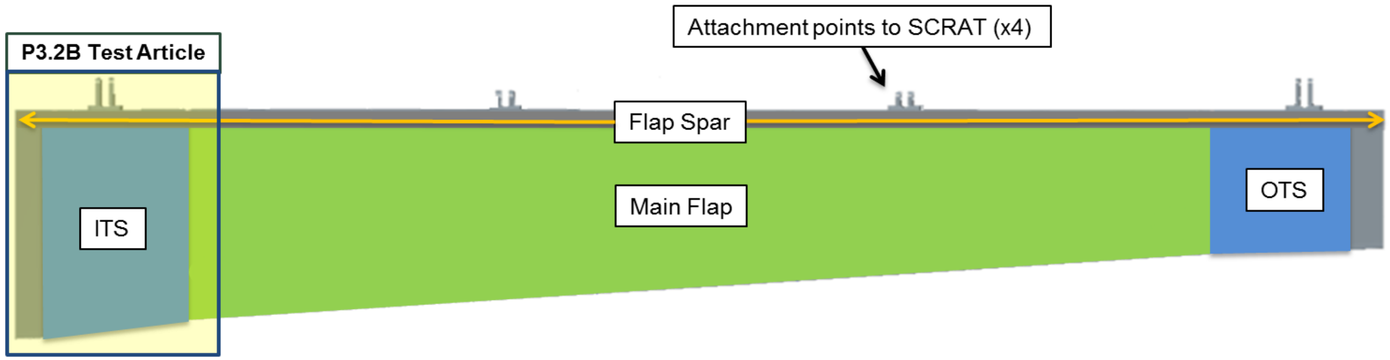


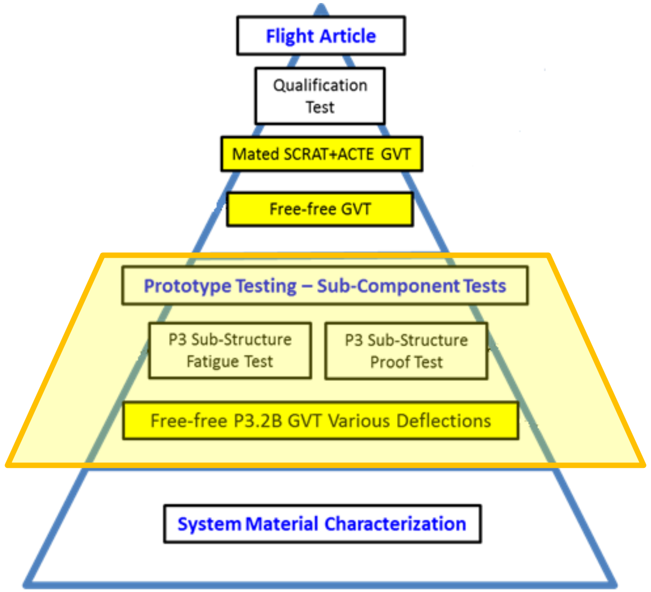


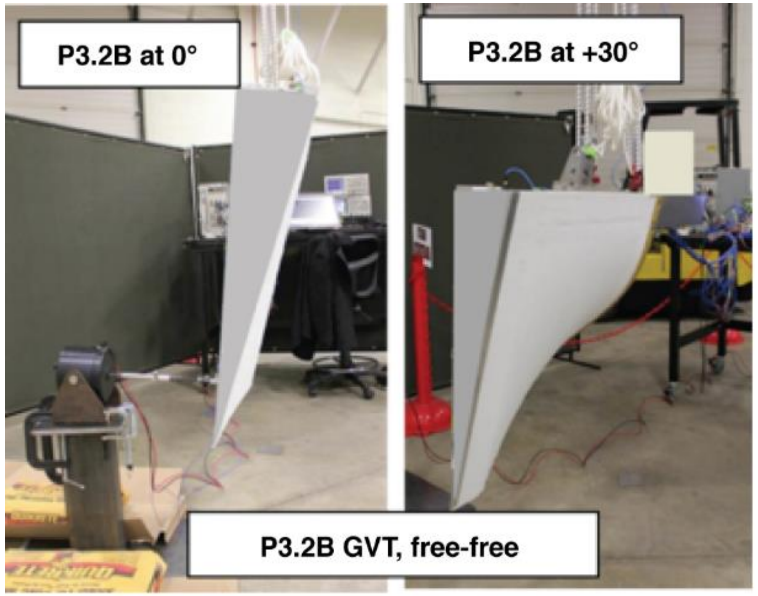
Ground Testing Approach

Prototype - P3.2B Ground Vibration Testing

- Objective: to measure modal characteristics at -2°, 0°, and +30°
- Test article: P3.2B (full-scale, right-side ITS)
- Analyzed in two steps
  1) Deflection of FEM by FlexSys' inputs.
  2) Modal analysis on deflected FEM
- An equivalent Young's modulus in a linearized non-linear structural analysis
- The test objectives were:
  1) Quantify change in frequencies and mode shapes as a function of flap deflection with the test article in a free-free boundary condition
  2) Evaluate analytical FEM techniques employed
  3) Determine which FEM software (ANSYS® vs. Nastran™) is more accurate in analytically deflecting the ACTE flap to best represent the ACTE structural modes
  4) Evaluate various types of excitation methods
  5) Determine what design variables to use in potential future FEM updates
- Only free-free boundary condition







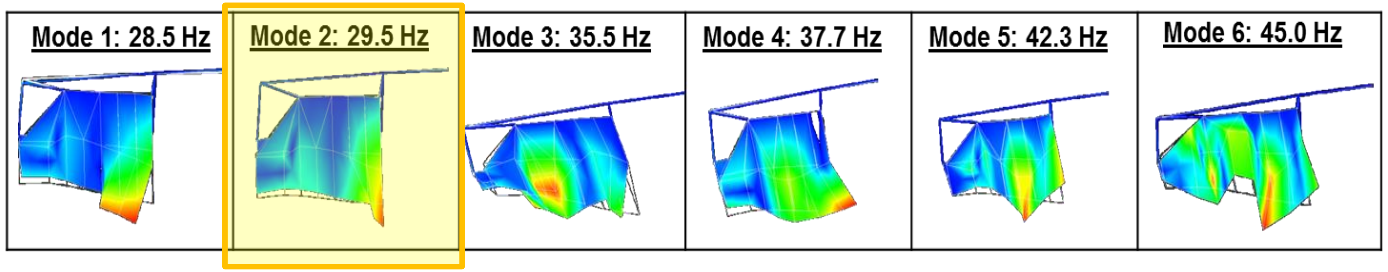
Ground Testing Approach

P3.2B Ground Vibration Testing

- Lessons Learned and Observations
  1) Comparison of ANSYS® vs. Nastran™ deflected FEM
  2) Good comparison to GVT results from ANSYS®
  3) Analytical results lower than GVT results for critical modes
  4) Post-test FEM update not required
  5) Significant effect on the mode shapes and frequencies by deflecting and applying an internal load
  6) Required multiple types of excitation
  7) Unexpected outcomes - Unpredicted mode observed at 30 degs due to lack of stiffness caused by missing main flap section; high damping levels
- Decrease in frequencies as a function of increased deflection
- Observations from GVT informed the planning of the full flap GVT
- Correlation of GVT results to analytical predictions informed the model update of the full flap FEM

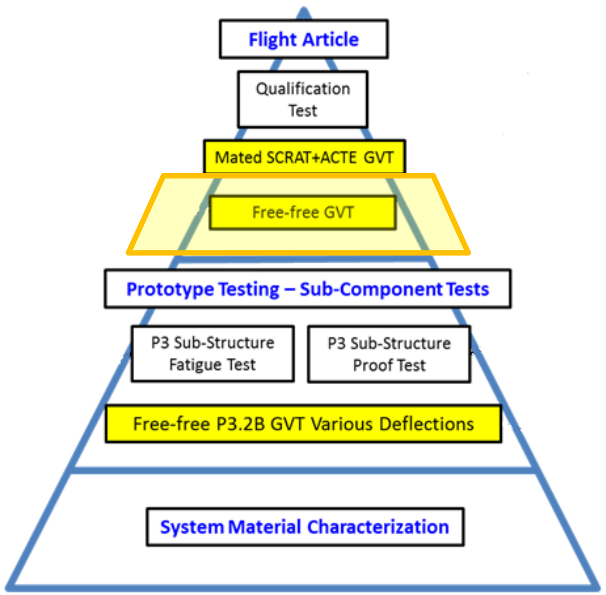
Unpredicted mode non-existent in other deflections

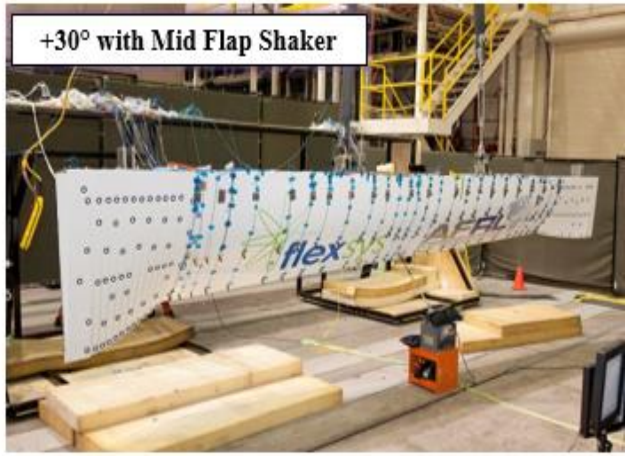
Mode	-2° (Up)			0° (Wing OML)			30° (Down)		
	Test (Hz)	FEM (Hz)	% Change	Test (Hz)	FEM (Hz)	% Change	Test (Hz)	FEM (Hz)	% Change
1	31.4	27.2	-13.3%	31.1	26.8	-13.8%	28.5	29.6	4.1%
2	---	---	---	---	---	---	29.5	---	---
3	38.2	33.5	-12.3%	37.0	33.1	-10.6%	35.5	31.7	-10.7%
4	42.3	39.3	-7.0%	42.1	38.8	-7.8%	37.7	37.4	-0.8%
5	46.4	45.1	-2.8%	46.2	44.5	-3.8%	42.3	44.5	5.3%
6	50.4	46.5	-7.8%	50.4	46.6	-7.4%	45.0	45.3	0.8%



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
- Test objectives were to:
  1) Verify expected trend in frequencies as a function of deflection
  2) Acquire the data to validate and update the flap FEM for 0°, +15° and +30° flap deflections
  3) Acquire weight and CG measurements for the flight article
  4) Evaluate various non-contact sensing methods for acquiring GVT data
     1) Laser Doppler vibrometer
     2) Photogrammetry

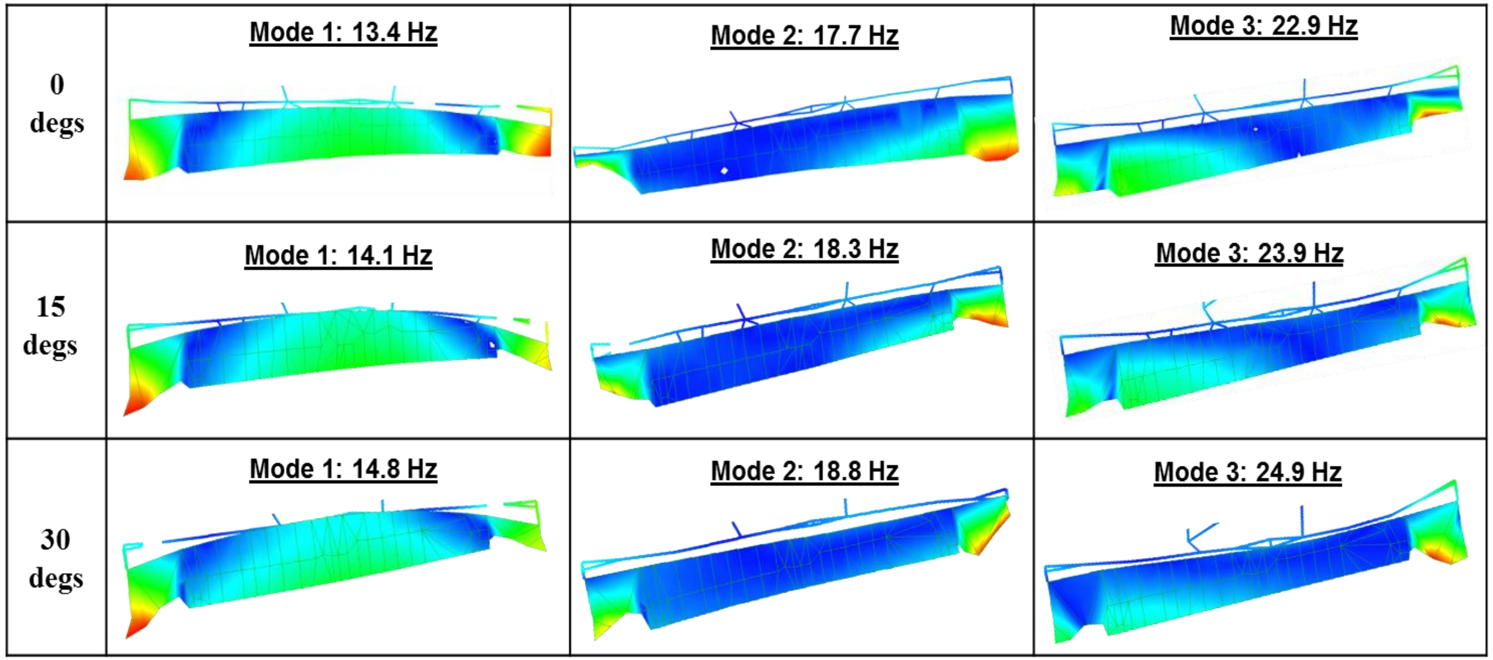


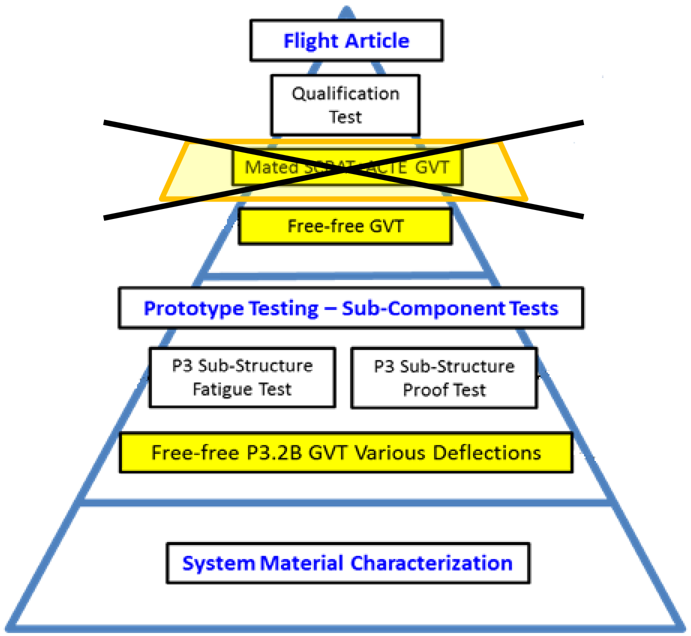


Ground Testing Approach

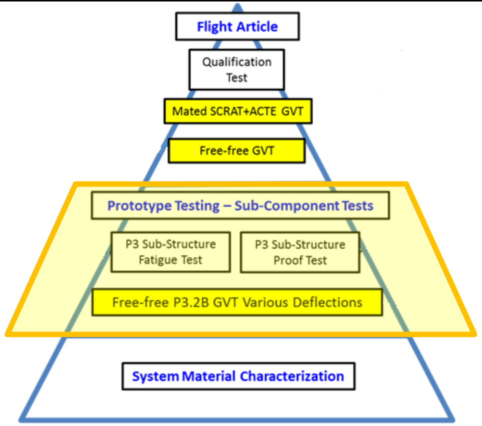
- **Flight Article Right Flap GVT Results**
  - Increase in frequencies as a function of deflection
  - Only first three modes captured based on frequency range of flutter analysis
  - Flight test instrumentation locations on the transition sections decided by mode shapes.
  - Acquisition of data required to perform FEM update.

- **Updated flutter analysis led to foregoing of the last GVT, the Mated SCRAT/ACTE GVT**



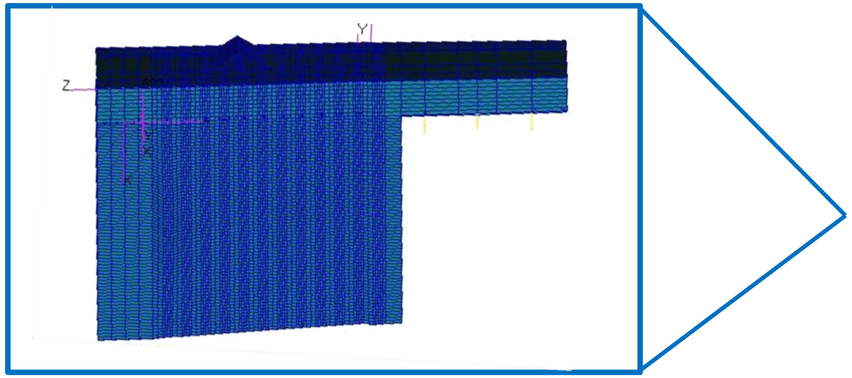


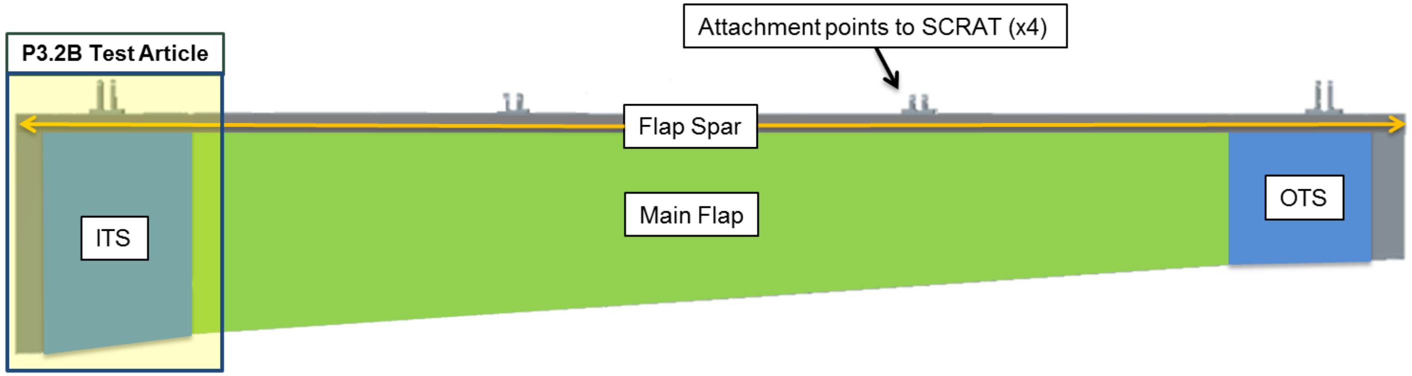
Aeroelastic Analysis



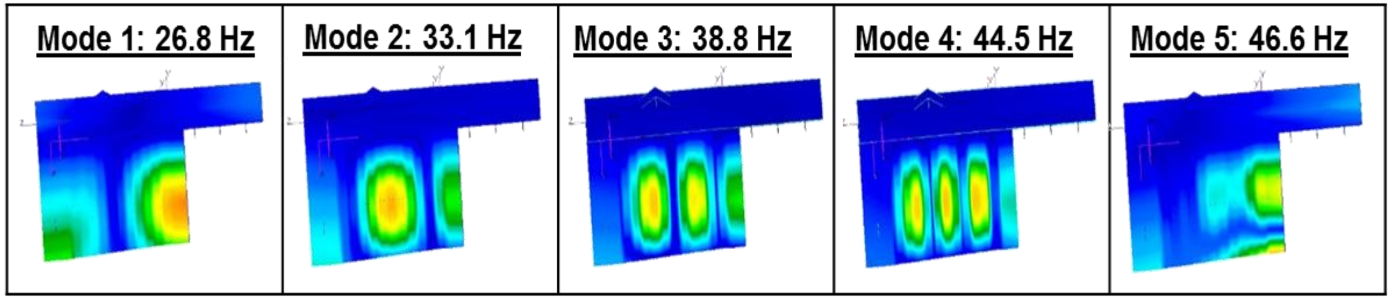
Prototype Model Correlation

- P3.2B FEM 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





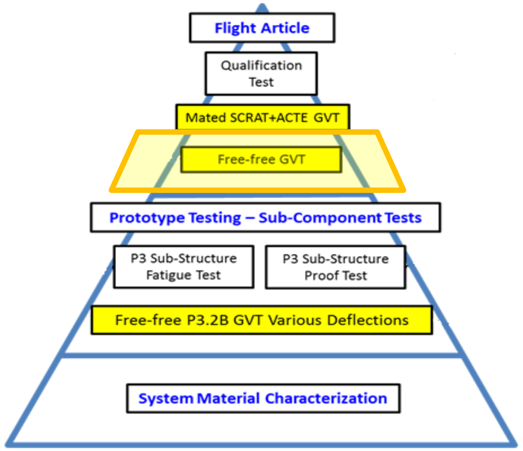
Mode	-2°	0° (Wing OML)	30°
1	27.2	26.8	29.6
2	33.5	33.1	31.7
3	39.3	38.8	37.4
4	45.1	44.5	44.5
5	46.5	46.6	45.3



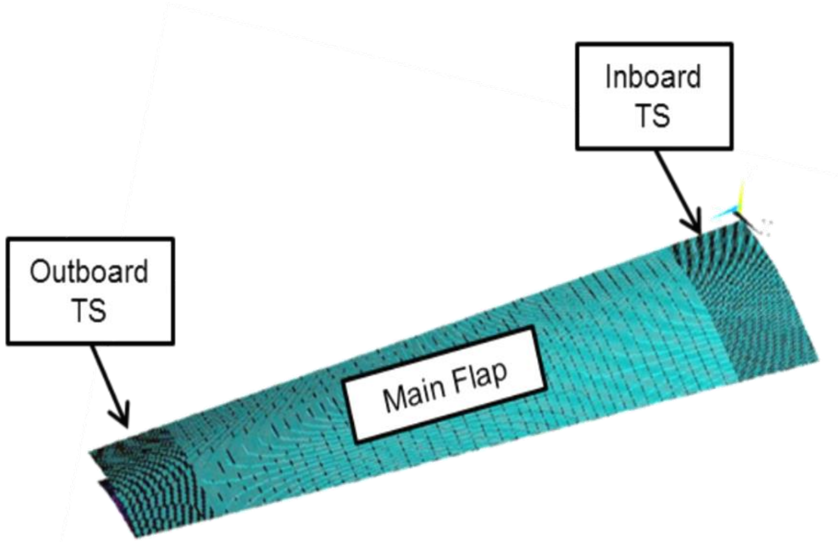
Aeroelastic Analysis

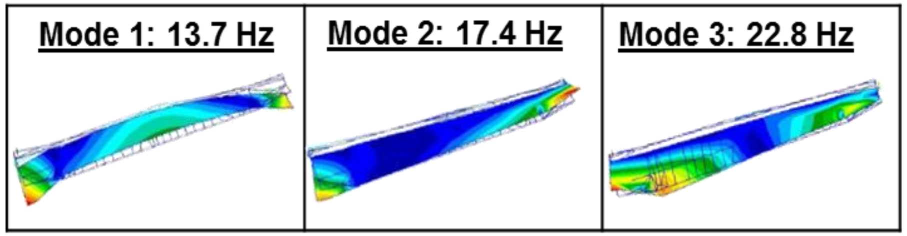
Flight Article Model Update

- Linearized analysis
  - Material properties validated by P3.2B GVT; applied to TS of the full flap FEM
  - An individual FEM for each deflection
  - FEMs updated to match GVT results
  - Compliance to FEM update requirements (NASA-STD-5002)
- Analytical mode shapes and frequencies from Nastran
- General increase in frequencies versus increasing deflection



Mode	0° (Wing OML)	15°	30°
1	13.7	14.1	14.9
2	17.4	18.5	19.2
3	22.8	23.8	23.8





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%

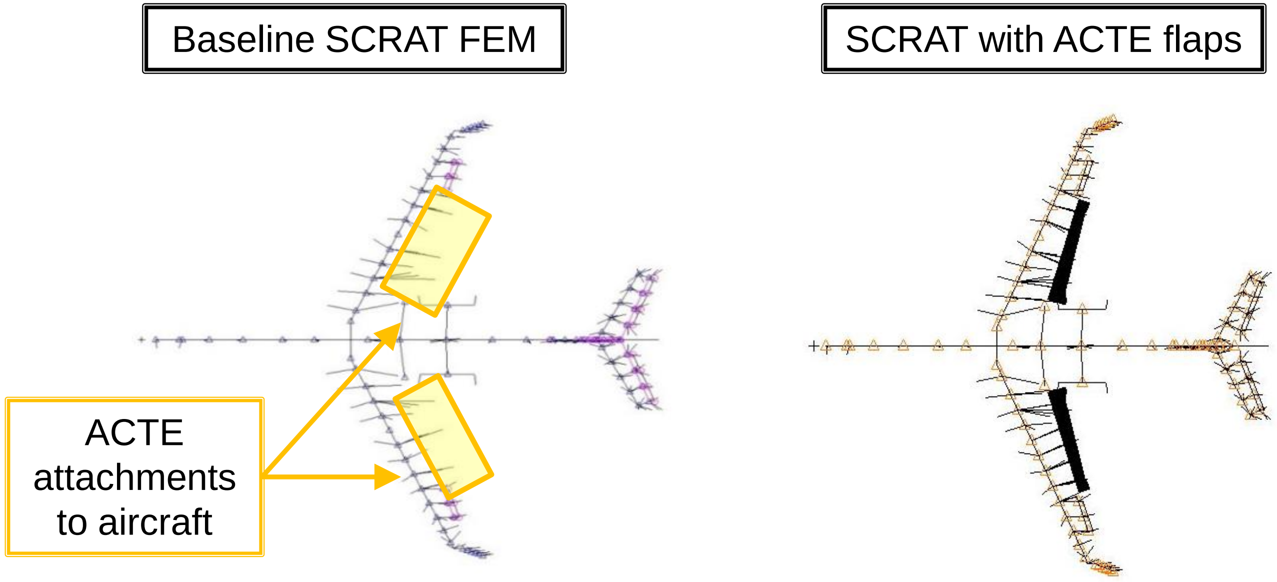
Aeroelastic Analysis

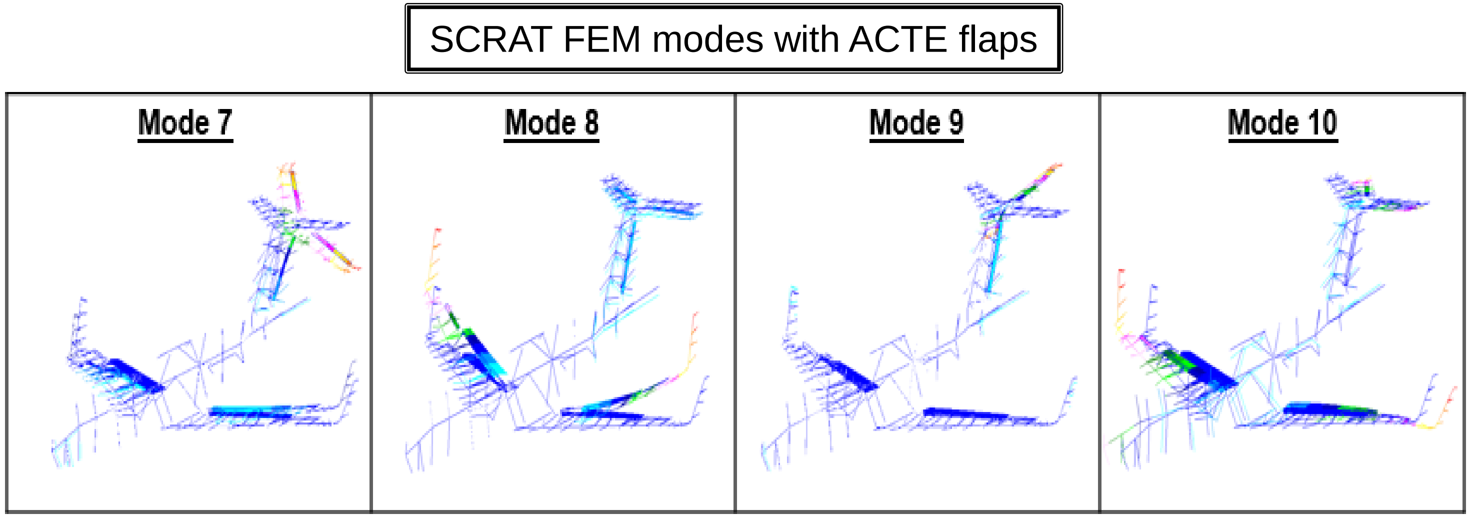
Pre-flight Analytical Predictions

- Provided trends across flight envelope and informed flight-testing
- Development of structural and aero models for two fuel conditions and various flap deflections

Structural Modal Analysis

- Model integration and analysis using Nastran
- GVT-correlated SCRAT empty/full fuel FEMs baseline aircraft GVT
- SCRAT modeled as simple stick model
- Fowler flaps modeled as point masses
  - Removed for integration of ACTE
  - Attachments to aircraft modeled as spring elements

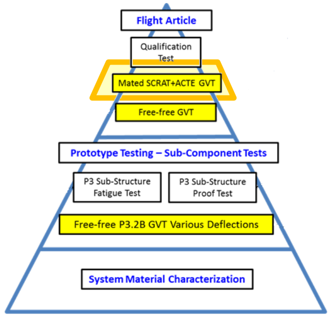


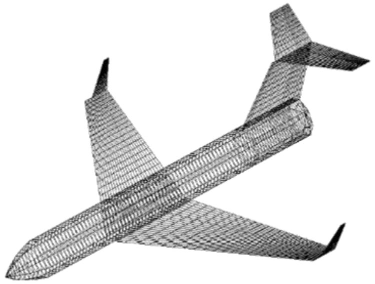


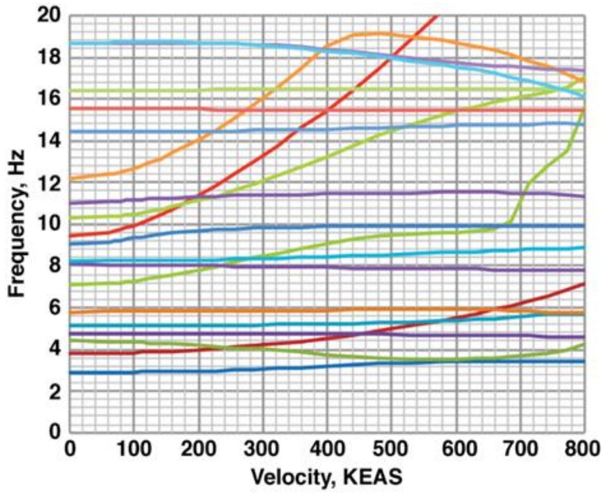
Aeroelastic Analysis

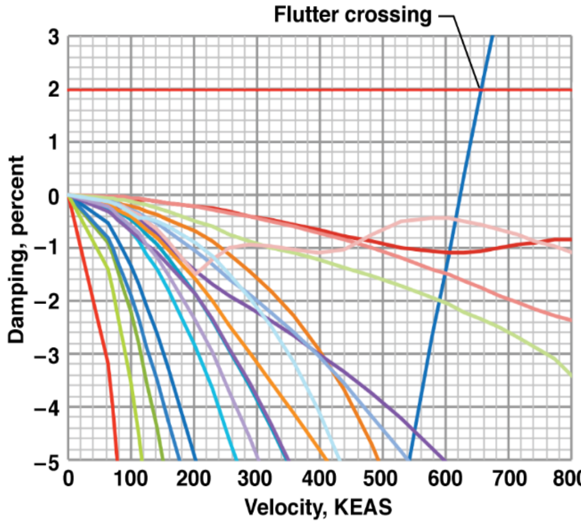
Flutter Analysis

- Performed using the ZAero code
  - Matched point analysis
  - Mach numbers 0.6, 0.7, and 0.8
- Encompassed full fuel and empty fuel conditions with the ACTE flaps at various deflections
- Flutter crossing at 2.0% damping
- High flutter margins
  - Sensitivity analysis was also done with varying spring connection stiffness values
- Show flutter speeds increase with increasing flap deflection
- Provided frequencies that can be compared against flight measurements









Flap angle	Mach = 0.6 Speed (KEAS)	Mach = 0.6 Frequency (Hz)	Mach = 0.6 Altitude (ft)	Mach = 0.7 Speed (KEAS)	Mach = 0.7 Frequency (Hz)	Mach = 0.7 Altitude (ft)	Mach = 0.8 Speed (KEAS)	Mach = 0.8 Frequency (Hz)	Mach = 0.8 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	Mach = 0.6 Speed (KEAS)	Mach = 0.6 Frequency (Hz)	Mach = 0.6 Altitude (ft)	Mach = 0.7 Speed (KEAS)	Mach = 0.7 Frequency (Hz)	Mach = 0.7 Altitude (ft)	Mach = 0.8 Speed (KEAS)	Mach = 0.8 Frequency (Hz)	Mach = 0.8 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

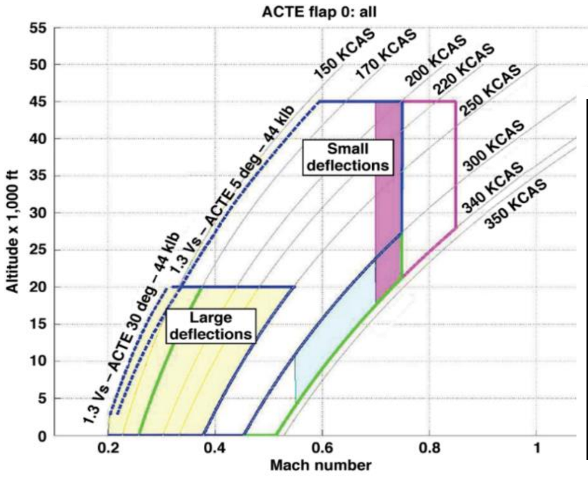
Flight Testing Approach

Pre-flight Frequency Predictions

- Developed for each fuel condition/flap deflection.
  - Anchor points: Frequencies as a function of dynamic pressure for flap deflections analyzed
  - Spot checks: Frequency trends as a function of flap deflection

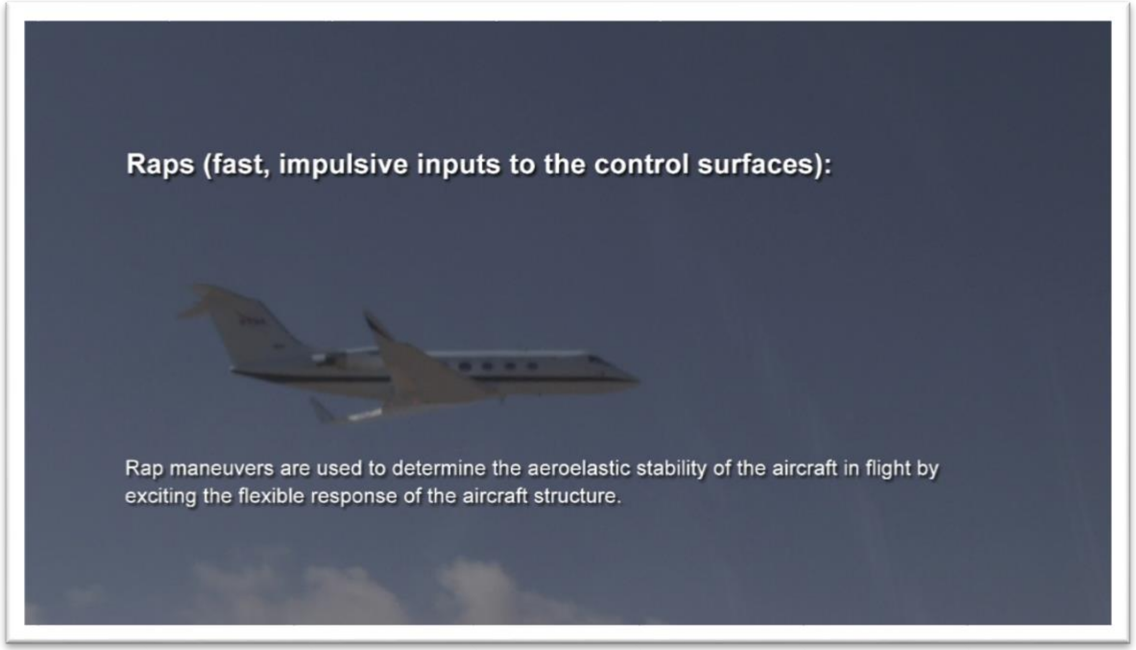
Project Approach

- Build-up approach
  - Low/slow => high/slow => high/fast => low/fast
  - Small deflections => max Mach and max dynamic pressure conditions
  - Large deflections => reduced envelope, M0.55
- Safety chase usage
- Staffed AFRC control room
- Wide-ranging suite of flight test maneuvers
  - 2-1-1’s, Wind-up turns, POPU, raps, etc.
  - Raps excited low frequency modes
  - A variety of other maneuvers excited higher frequency modes: 2-1-1’s, turbulence and other anti-symmetric maneuvers



Pre-flight Analytical Predictions for ACTE 0°

SCRAT EMPTY FUEL/ACTE 0° CONFIGURATION		SCRAT FULL FUEL/ACTE 0° CONFIGURATION	
Description	Frequency (Hz)	Description	Frequency (Hz)
ACTE ITS symm	19.3	ACTE ITS symm	18.4
ACTE ITS anti	19.3	ACTE ITS anti	16.5
ACTE OTS symm	21.8	ACTE OTS symm	20.1
ACTE OTS anti	23.2	ACTE OTS anti	20.2



Flight Testing Approach

Transition Section Results

- Transition section instrumentation determined by motion observed in mode shapes
- Right side instrumentation mirrored on left side
- Monitored all accelerometers
- Strain gages sampled at 1000 Sa/sec for monitoring
- InterActive Display Software (IADS) software usage:
  - Monitor data
  - Calculate PSDs
  - Perform HPD estimations.
- High frequencies tracked for panel-type responses

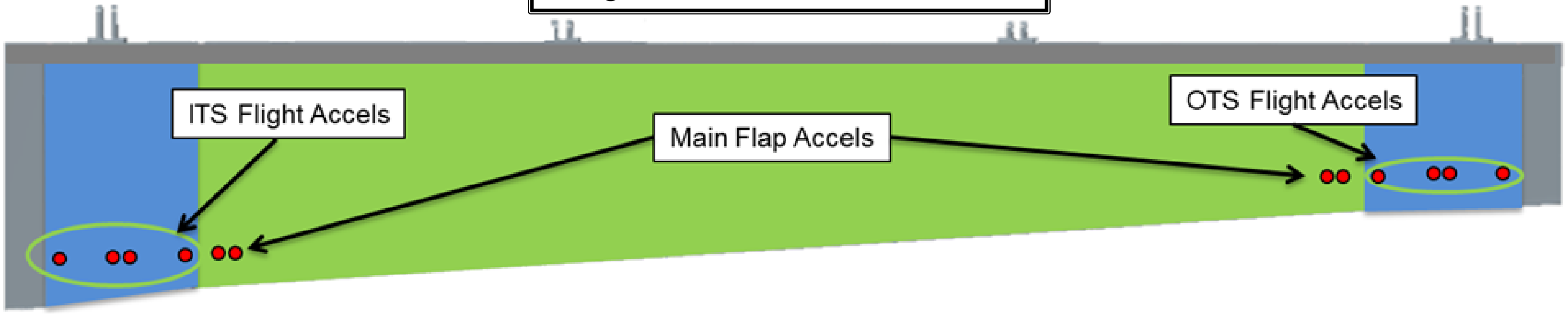
TS flight-test response for ACTE 0°

		Left Side Flap		Right Side Flap	
Mode	Description	Flight Freq. (Hz)	Damping (%)	Flight Freq. (Hz)	Damping (%)
1	ACTE ITS symm	19.1	2.4%	19.3	8.3%
2	ACTE ITS anti	18.3	7.4%	18.3	5.5%
3	ACTE OTS symm	21.4	6.3%	21.4	4.5%
4	ACTE OTS anti	22.4	11.8%	22.4	7.6%

Right TS High frequency response

Transition Section	Sensor	Freq. (Hz)
ITS	FL2006A	282.8
OTS	FL2016A	241.6
OTS	FL2016A	282.8

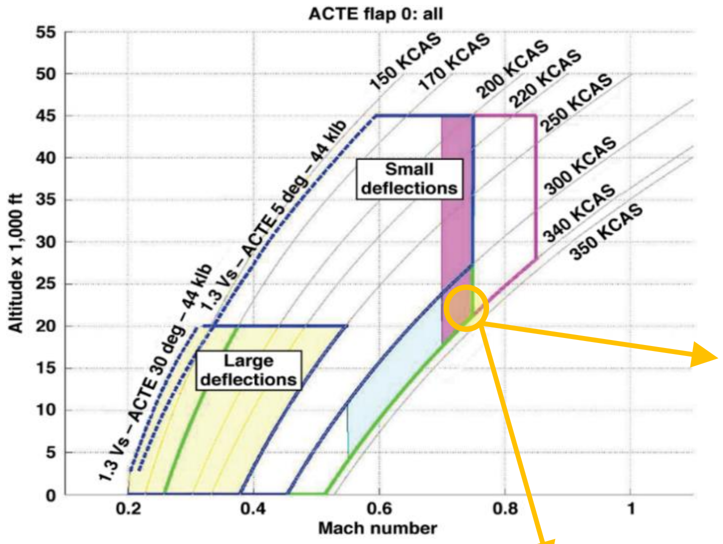
Right ACTE Instrumentation



Flight Testing Approach

Age old battle: Analysis versus Test

- Anchor point results compared directly to analysis
- Spot check results for result trend comparisons
- Good correlation for ITS and OTS low frequency results
  - Were in line with empty/full fuel values, considering the fuel and flight condition variations
- Similar good correlation for ITS and OTS high frequency results
  - Multiple frequencies were measured
  - No gross deviations from analytical predictions



Right TS High frequency response

Sensor	Flight	Analysis
FL2006A	282.8	
FL2016A	241.6	295
FL2016A	282.8	

TS analysis/test comparison for 0°

Description	Analytical Empty Fuel Freq. (Hz)	Left Side Flight Freq. (Hz)	Right Side Flight Freq. (Hz)	Analytical Full Fuel Freq. (Hz)
ACTE ITS symm	19.28	19.1	19.3	18.44
ACTE ITS anti	19.34	18.3	18.3	16.45
ACTE OTS symm	21.8	21.4	21.4	20.05
ACTE OTS anti	23.2	22.4	22.4	20.23

Summary and Conclusions

- Successful structural integration of two non-conventional control surfaces into an existing testbed
- Need for non-linear analysis created by large deflections applied to compliant structure
- Build-up ground testing approach applied:
  - Allowed for investigation and validation of ground test techniques
  - Validated modeling and analysis methods
- A set of TS testing/FEM development iterations was exercised
  - Development of accurate flight article FEM
  - Ensured accurate final flutter analyses
- Final flutter analyses were performed:
  - Showed compliance with the 20% flutter margin requirement
  - Development of pre-flight flutter predictions for the flight test campaign
- Flight test results used to complete airworthiness process.
  - Various types of comparisons performed
  - Analysis to test comparison showed acceptable results
- Follow-on work is being planned:
  - Extension of Mach
  - Acoustic signature evaluation
- Potential to reveal unstable panel responses