Aeroelastic Response of the Adaptive Compliant Trailing Edge Transition Section

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The Adaptive Compliant Trailing Edge demonstrator was a joint task under the Environmentally Responsible Aviation Project in partnership with the Air Force Research Laboratory and FlexSys, Inc. (Ann Arbor, Michigan), chartered by the National Aeronautics and Space Administration to develop advanced technologies that enable environmentally friendly aircraft, such as continuous mold-line technologies. The Adaptive Compliant Trailing Edge demonstrator encompassed replacing the Fowler flaps on the SubsoniC Aircraft Testbed, a Gulfstream III (Gulfstream Aerospace, Savannah, Georgia) aircraft, with control surfaces developed by FlexSys, Inc., a pair of uniquely-designed, unconventional flaps to be used as lifting surfaces during flight-testing to substantiate their structural effectiveness. The unconventional flaps consisted of a main flap section and two transition sections, inboard and outboard, which demonstrated the continuous mold-line technology. Unique characteristics of the transition sections provided a challenge to the airworthiness assessment for this part of the structure. A series of build-up tests and analyses were conducted to ensure the data required to support the airworthiness assessment were acquired and applied accurately. The transition sections were analyzed both as individual componenets and as part of the flight-test article assembly. Instrumentation was installed in the transition sections based on the analysis to best capture the in-flight aeroelastic response. Flight-testing was conducted and flight data were acquired to validate the analyses. This paper documents the details of the aeroelastic assessment and in-flight response of the transition sections of the unconventional Adaptive Compliant Trailing Edge flaps.

Nomenclature

ACTE	=	Adaptive Compliant Trailing Edge
AFRC	=	Armstrong Flight Research Center
AFRL	=	Air Force Research Laboratory
CFD	=	computational fluid dynamics
CG	=	center of gravity
E	=	Young's Modulus, lbs/ in^2
ERA	=	Environmentally Responsible Aviation
FEM	=	finite element model
FLL	=	Flight Loads Laboratory
GIII	=	Gulfstream III aircraft
GAC	=	Gulfstream Aerospace Corporation
GVT	=	ground vibration test
HPD	=	half power damping
IADS	=	Interactive Analysis and Display Software
ITS	=	inboard transition section
KCAS	=	knots calibrated airspeed
KEAS	=	knots equivalent airspeed
MCC	=	Mission Control Center
NASA	=	National Aeronautics and Space Administration

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OML = outer mold line
OTS = outboard transition section
P2 = Prototype 2 series
P2.2B = Prototype 2.2B
P3 = Prototype 3 series
P3.2B = Prototype 3.2B
PSD = power spectral density
SBIR = Small Business Innovation Research
SCRAT = SubsoniC Research Aircraft Testbed
S-S = stress-strain
TN = tail number
TRL = technology readiness level
TS = transition section

I. Introduction

IN 1998 the Air Force Research Laboratory (AFRL) began supporting the development of adaptive compliant wing technology through the Small Business Innovation Research (SBIR) program with FlexSys, Inc. (Ann Arbor, Michigan) using various wing leading and trailing edge designs.[1-5] Numerous studies and flight-test demonstrations have shown the aerodynamic benefits of an adaptive airfoil;[6-9] however a full-scale flight demonstration was needed to establish confidence in and advance the technology readiness level (TRL) for an adaptive, compliant structure with a continuous mold-line. This capability would be used to further the goal of National Aeronautics and Space Administration (NASA) to develop compliant structure technologies that provide structural load alleviation, increase control surface effectiveness, and improve aerodynamic efficiency and noise reduction. In late 2009, AFRL and the NASA Environmentally Responsible Aviation (ERA) project partnered to provide a Gulfstream III (GIII) aircraft (Gulfstream Aerospace Corporation, Savannah, Georgia) for integration and flight research of an Adaptive Compliant Trailing Edge (ACTE) flap technology designed and built by FlexSys. This joint partnership lead to a successful ACTE flight-testing campaign in 2015 through incorporating FlexSys proprietary technology as a full-scale flight demonstration of an adaptive, compliant structure with a continuous mold-line surface integrated onto the NASA Armstrong Flight Research Center (AFRC) (Edwards, California) GIII SubsoniC Research Aircraft Testbed (SCRAT),[10] TN804, as shown in Fig. 1. The ACTE flaps were flown at deflections ranging from -2° (up) to +30° (down) in order to validate the structural effectiveness of the ACTE during flight-testing. All parties contributed to different aspects of the ACTE program: the AFRL and NASA ERA were responsible for ensuring that the compliant structure technology matured, FlexSys was responsible for the compliant flap design, and NASA AFRC was responsible for systems integration and flight-test execution. The NASA AFRC airworthiness process was followed to ensure all ACTE safety-of-flight aspects were met.

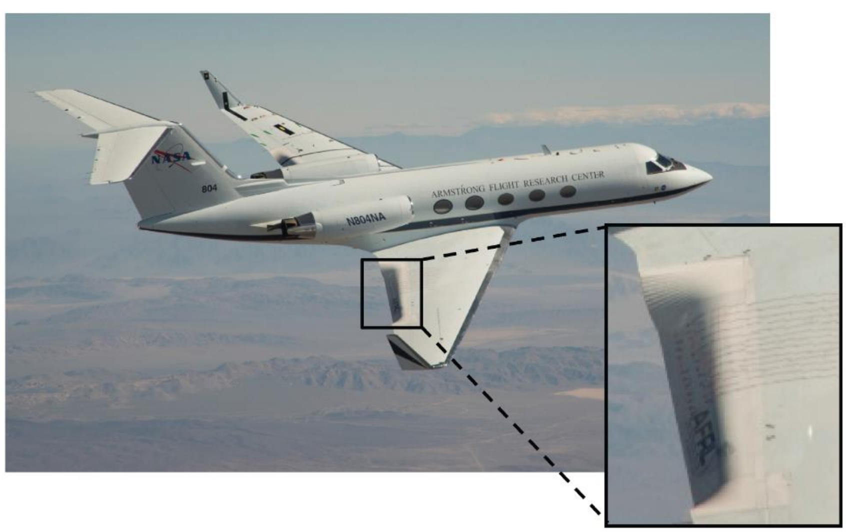


Figure 1. The ACTE flaps at 25 ° deflection flown on the SCRAT.

The aeroelastic effects of integrating the ACTE flight article were evaluated to ensure the combined SCRAT/ACTE system was safe to fly within the flight envelope desired for the ACTE project. Per NASA AFRC aeroelastic guidelines, the SCRAT/ACTE system needed to show a 20% flutter margin to satisfy the project requirements for demonstration of airworthiness. To support the demonstration of sufficient flutter margin, a finite element model (FEM) was developed and validated by data acquired from performing a ground vibration test (GVT). To minimize the impact to the flight schedule and attempt to accurately model the flight article, a build-up test and analysis approach was developed using prototype test articles. This structural building block test and analysis approach ensured an advanced understanding of the dynamic response of the FlexSys innovative compliant structure. Smaller span-wise prototype test articles representative of the ACTE flap were built prior to the flight articles and were used for this build-up ground testing approach.[11] Unique characteristics of the transition sections provided a challenge to the airworthiness assessment for this part of the ACTE structure, and that process will be discussed in detail in this paper. The continuous mold-line provided by the transition sections were analyzed as part of the whole ACTE flight-test article. Instrumentation was installed in the transition sections based on the analysis to best capture the in-flight aeroelastic response. Flight-testing was conducted, and flight data were acquired to validate the pre-flight analyses. This paper documents the ground testing and analysis effort for the aeroelastic airworthiness assessment and in-flight response of the continuous mold-line technology demonstrated through the transition sections of the FlexSys unconventional ACTE flaps.

II. Test Article

A. Overview of ACTE Flaps

The ACTE flight-test article consisted of two ACTE flaps that replaced the NASA SCRAT Fowler flaps and flight and ground spoilers. The ACTE flight article consisted of five main components: the inboard transition section (ITS), the outboard transition section (OTS), the main flap section, the flap spar, and the actuation system. The actuation system was not exercised in flight. Instead each flap was set to a pre-determined position on the ground before every flight. The ACTE flaps actuated from -2° (up) to +30° (down), relative to the fixed wing portion. The ACTE flap provides a seamless continuous mold line. This characteristic is shown in Fig. 2 as well as the inboard and outbard transition sections.

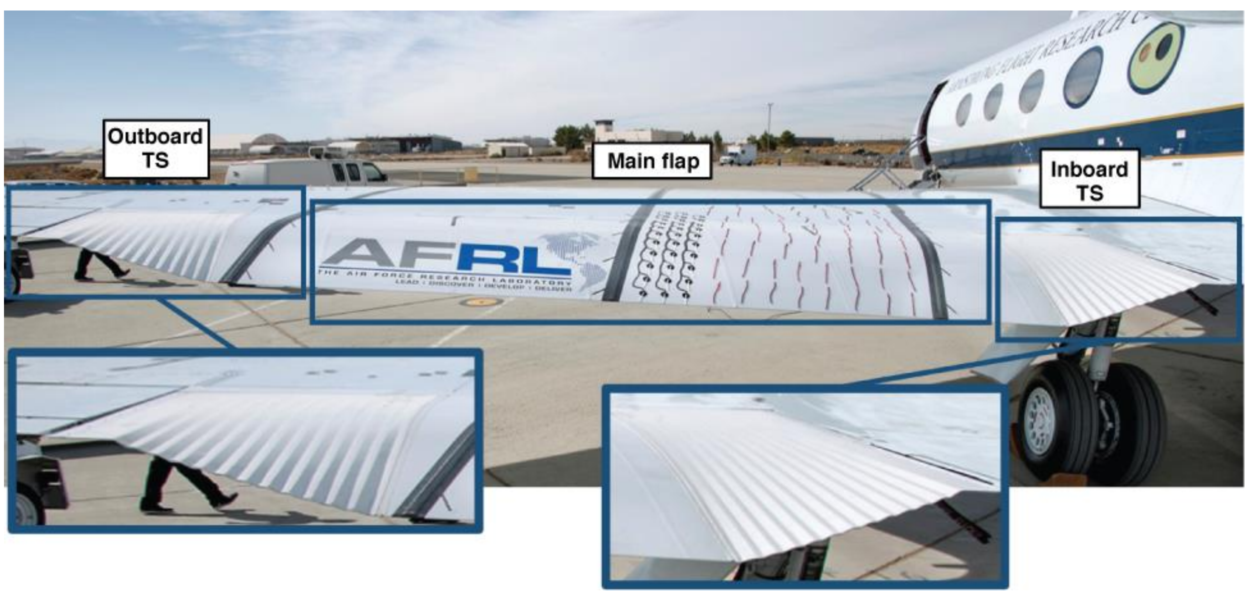


Figure 2. ACTE flight article.

B. Importance of the Transition Sections

In order to provide the seamless continuous mold line between the main flap section and the aircraft wing, each ACTE flap contained an ITS and OTS. The transition sections (TS) were used to transition in a stepwise, accordion fashion from the deflected main flap section to the fixed wing outer mold line (OML). When the main flap is actuated, the transition sections gradually deform spanwise demonstrating the seamlesss continuous mold-line technology. The inboard and outboard transition sections are similar in construction, but differ in size based on the SCRAT wing taper. In order to successfully provide the capability of compliance, the structure of the transition section had to be flexible, but strong enough to carry the aero load experienced during flight. The airworthiness of the transition sections needed to be assessed and certified. Due to the large deformations experienced by these structures, the assessment of these components required non-linear modeling and analysis techniques.

Part of the airworthiness assessment was to perform a computational fluid dynamics (CFD) analysis of the ACTE installed on the SCRAT to determine its effects on the flight dynamics of the aircraft. The CFD analysis of the combined SCRAT/ACTE system showed a potential for supersonic flow over the ACTE flap at the higher Mach numbers, which increased the probability of structural failure of the ACTE flaps. As a result, in addition to tracking the classical flutter modes of the aircraft and ACTE during flight-testing, special attention was given to high frequency panel-type responses of the transition sections.

III. Ground Testing

Ground testing was one essential aspect of the ACTE project development approach which incorporated conventional design practices and a buildup test and model validation approach. Numerous ground tests were conducted over the life cyle of the ACTE project to ensure airworthiness of the structure and help mitigate risk to schedule and mission success. These ground tests consisted of material characterization testing, structural proof testing, structural qualification testing, fatigue testing, and ground vibration testing. GVTs were conducted to obtain the modal characterization of the transition sections and to determine best practices for testing of the flight article.

A. Build-up Approach

The project employed a build-up approach to ground testing so that design and fabrication flaws could be detected and corrected early in the project life-cycle process in order to minimize major schedule delays and cost increase. This building block approach also provided the opportunity for the project team to gain early fundamental insight into the compliant structure technology. Finite element models were validated as part of this approach, building confidence in the modeling approach. Prototype test articles representative of the ACTE flap design and fabrication process were built prior to the flight articles and were used for this build-up approach to ensure the data required to support the airworthiness assessment was acquired and applied accurately to the flight article. There were two sets of prototype test articles designated Prototype 2 (P2) and Prototype 3 (P3) prior to the ACTE flight articles. Each prototype contained two components designated as “A” or “B.” Prototype test articles designated “A” were representative of a portion of the main flap section, and prototypes designated “B” were full-scale chordwise TS. A pictorial presentation of the build-up testing approach is shown in Fig. 3 with the planned structural dyanmics tests required for the aeroelastic airworthiness assessment highlighted. Confidence in the aeroelastic analyses was increased by also incorporating data from the other structural tests performed.

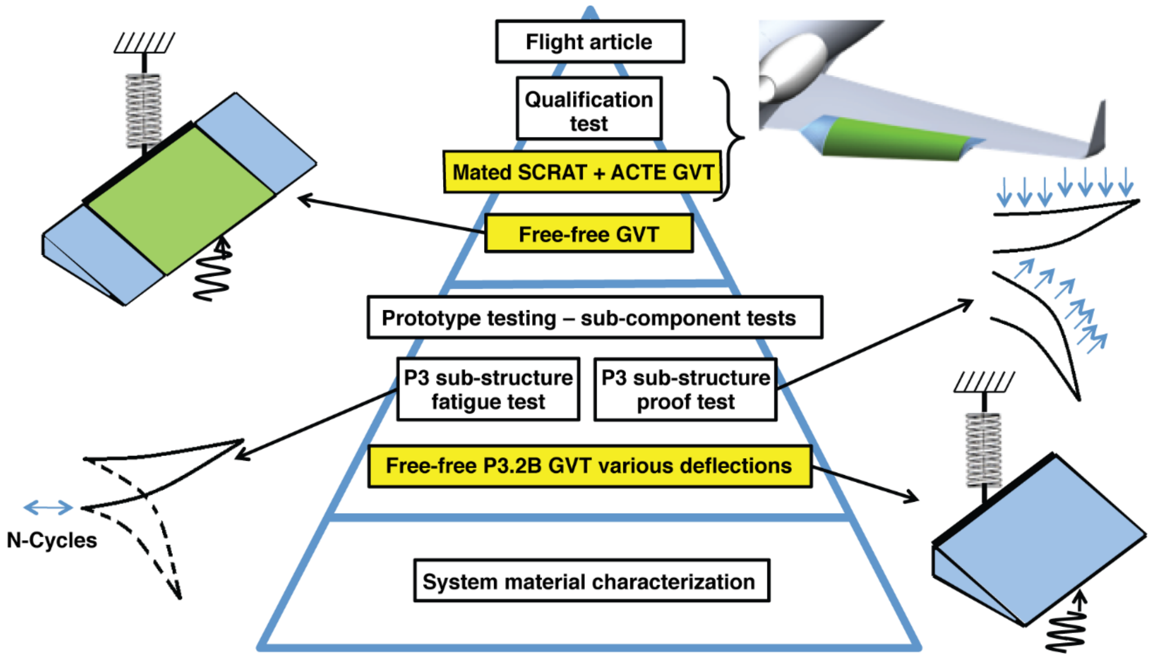


Figure 3. ACTE building block testing approach.

B. Prototype Ground Vibration Testing

The differences between prototype P2 and P3 were some minor design, fabrication, and manufacturing process changes which allowed P3 to minimize strain levels for large deflections. The P3 design possessed the full chord-wise size of the flight-test article, but was only a section of span-wise size.

There were two prototype GVTs, Prototype 2.2B (P2.2B) and Prototype 3.2B (P3.2B), performed prior to the flight article GVT to gain confidence in testing and understanding the modal characterists of the TS needed for the FEM development and validation. Both prototypes were representations of the right side ITS with some slight differences. P2.2B did not possess the SCRAT wing taper in its geometry, but did include a section of the flap spar, an inboard section that represented the SCRAT wing, and an outboard section that represented the main flap. P3.2B included the wing taper and was a duplicate of the right side ITS.

1. Prototype 2.2B GVT

Prototype 2.2B was the first prototype to be tested. This prototype is not included in the build-up pyramid since it was not in the original ground test plan. The opportunity arose to perform this initial GVT as a proof of concept for testing a compliant structure. The P2.2B GVT was conducted by NASA personnel at the FlexSys facility in September 2012. The test goals were to measure the P2.2B test article frequencies and mode shapes at several deflections and two boundary conditions. The test objectives of P2.2B were as follows:

1) Consider any apparent change in stiffness of the structure due to changing the flap deflection.
2) Evaluate accelerometers as instrumentation on flexible structure.
3) Evaluate various types of excitation methods and instrumentation mass loading effects.
4) Evaluate analytical FEM techniques employed.

The P2.2B testing configurations conducted were both a cantilevered and free-free boundary condition with the TS deflected to -2°, 0°, and +30°. Figure 4 shows the P2.2B GVT setup in the cantilevered boundary condition by utilizing a heavy milling machine as the test supporting structure.

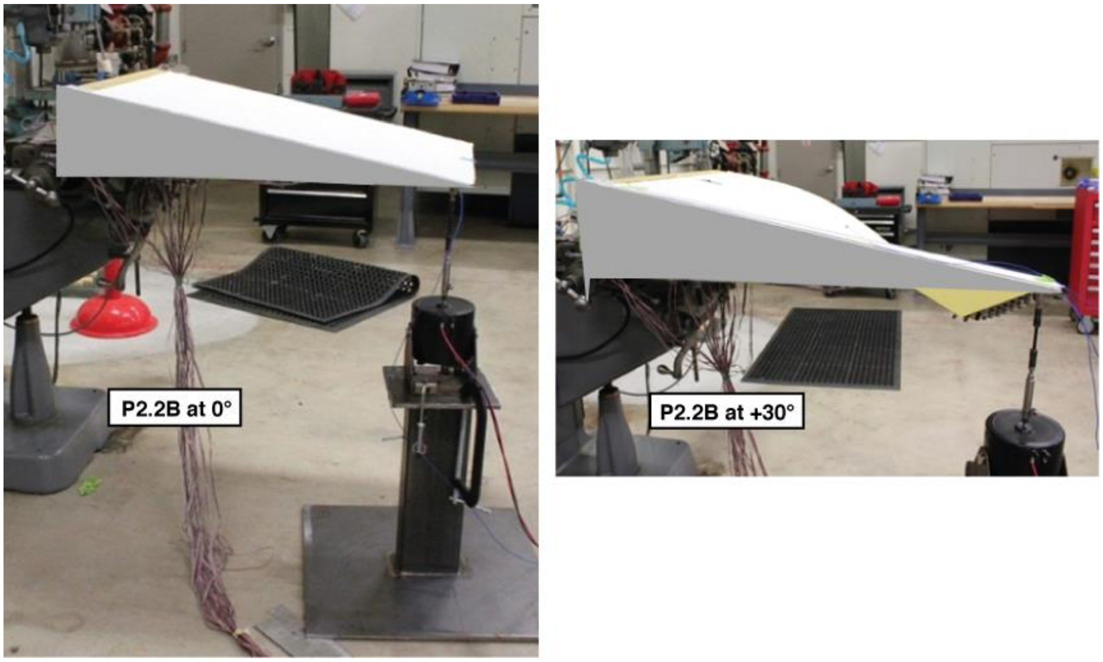


Figure 4. Prototype 2.2B cantilevered GVT setup.

Several lessons learned were captured from conducting the P2.2B GVT that helped plan for the follow-on testing. Results from the P2.2B GVT provided a comprehensive set of lessons learned on how to model the ACTE flap, how to test structures such as the ACTE flap, and helped identify possible design variables to update the FEM. This ground test was the initial opportunity to experimentally evaluate the structural dynamic response of the compliant flap structure, and various test techniques were explored. Some valuable lessons that were taken away from the P2.2B GVT were as follows:

1) The test structure (i.e. milling machine) must be instrumented and checked to verify modes will not couple with desired test article modes and frequencies. In general, test structure mass should be much higher than the test article mass to avoid coupling of the frequencies and mode shapes. However, local modes should be checked to verify no coupling occurs regardless of the difference in mass between the test structure and test article.
2) All structural and non-structural components should be modeled in the FEM regardless of boundary conditions. Some non-structural components were not modeled because they were located at the flap spar, which is where the test article was attached to the milling table. However, the mass contribution was significant enough that it merited to be modeled, and it was apparent in the GVT results.
3) Certain accelerometer locations are more capable of measuring the frequencies of the structural components of interest. The initial instrumentation layout covered the test article evenly. As the modes of interest were excited, it was quickly observed that accelerometers had to be relocated to better capture the mode shape. Mode shapes needed to be more distinct, which required certain locations without sensors to be instrumented.
4) Shaker excitation proved as effective as an impact hammer.
5) Best excitation location on the TS was applied at the fixed wing representative portion.

2. Prototype 3.2B GVT

The Prototype P3.2B GVT was the second TS tested by NASA personnel at FlexSys in April 2013. The test article was a reproduction of the right inboard TS of the ACTE flight article which had the largest chord on the ACTE flap. The P3.2B also had a 3-inch section that simulated the main flap section of the ACTE flight article, a 5.75-inch section to simulate the fixed wing section, and a truncated section of the ACTE flap spar. An attachment on the truncated spar section was used to simulate how the flap would connect to the SCRAT airframe. Figure 5 shows the section of the flight-test article represented by the P3.2B GVT article.

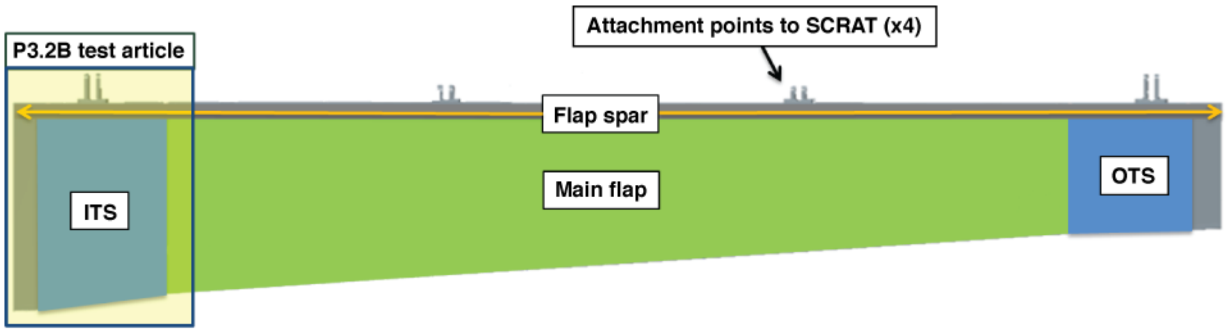


Figure 5. P3.2B test article.

The ACTE structure was analyzed for modal response in two steps. The first step deflected the ACTE FEM analytically to match the physical deflections of the structure. FlexSys developed a mathematical relation between the amount of input applied at the actuation points and the amount of flap deflection relative to the SCRAT fixed wing OML. The same inputs were applied at the actuation locations in the FEM. The second step analyzed the deflected structure for natural mode shapes and frequencies. Because of the large deformations experienced by the compliant structure, a non-linear analysis method was required. In order to simplify the analysis process, the non-linear analysis process was linearized. Deriving an equivalent Young's Modulus, E, as a function of deflection enabled this linear analysis. The experimental stress-strain (S-S) data was acquired from the system material characterization testing, and a non-linear analysis was performed on the TS to produce analytical frequencies and mode shapes. The equivalent Young's modulus was then determined based on the calculated frequencies and mode shapes.

The ACTE FEM was deflected analytically using both the ANSYS® (Canonsburg, Pennsylvania)[12] and Nastran™ (Newport Beach, California)[13] software packages. It was noticed that the resulting deflected FEMs did not match as well as expected. It was necessary to validate each of the deflected shapes against the measured deflected structure to determine, which software performed the best at creating the deflected FEM of the ACTE structure. The validation of the analytical deflected shapes against the measured deflected shapes became one of the objectives to be satisfied during the P3.2B GVT. The test objectives for the P3.2B GVT are listed below:

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.

Figure 6 shows the GVT setup with P3.2B in a free-free boundary condition which utilized an overhead suspension system made from bungees connected from the test article to the overhead ceiling rafters. The flap spar hardware was unobtrusively modified to include two attachment points for the overhead suspension system that straddled the span-wise P3.2B center of gravity (CG) location.

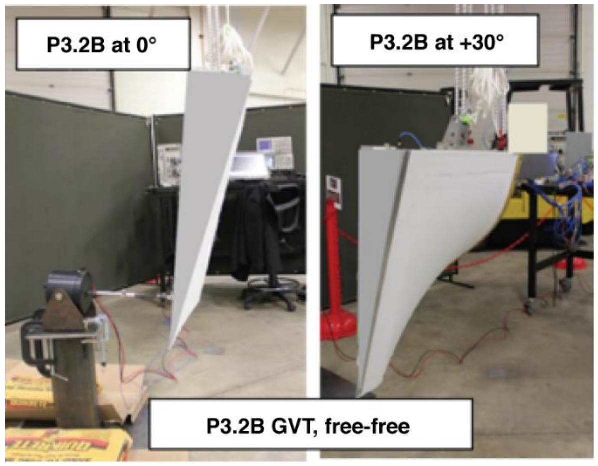


Figure 6. Prototype 3.2B free-free GVT setup.

A comprehensive set of lessons learned were captured from conducting the P3.2B GVT that were helpful for planning for the flight-test article on how to model the ACTE flap, how to test structures such as the ACTE flap, and how to update the FEM. The lessons learned from the P3.2B GVT were as follows:

1) The P3.2B GVT served to designate which analytical method (ANSYS® vs. Nastran™) produced more accurate analytical deflected flap shapes; ANSYS® deflection frequencies and mode shapes demonstrated a better match to GVT data.
2) Analytical mode shapes and frequencies calculated using the FEM deflected by ANSYS® compared well to GVT results as shown in Table 1 and in Fig. 7.
3) Analytical results were lower than GVT results for critical modes, which generally indicates conservatism in the flutter analysis if the analytical model was used as the FEM in the flutter analysis.
4) Post-test FEM update was not required, but was performed to have more accurate material properties for the flexible structure.
5) Geometry change caused by applying the different flap deflections had a significant effect on frequencies. The application of the various flap deflections changed the internal loading of the structure. The internal loading was significant enough to create an apparent change in stiffness that was manifested in the test frequencies and mode shapes
6) It was necessary to use multiple types of excitation at multiple locations to verify that the modes of interest as identified by the analysis were measured adequately. Burst random, sine sweep, and impact excitation profiles were applied at the simulated wing and simulated main flap sections. Data from all excitation types and locations were used to ensure the desired modes were captured well enough to use for model correlation. It was clear that most of the modes could be captured with a burst random applied at the simulated wing section. However, the data from other excitation types and the simulated main flap section provided supplemental data to confirm the modes measured and measure any additional modes.
7) There were some unexpected outcomes from the test. Due to some unique characteristics of the flexible structure, unexpectedly high damping values were empirically estimated. There was also an unpredicted mode for the +30° configuration that was revealed. This unpredicted mode is shown in line 2 of Table 1 and in Fig. 7. The truncated main flap section of the P3.2B in the span-wise direction, likely created a lack of stiffness in that direction for the highly deflected flap, which caused the mode to exist.

Table 1. P3.2B GVT versus analytical FEM data comparison.

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%

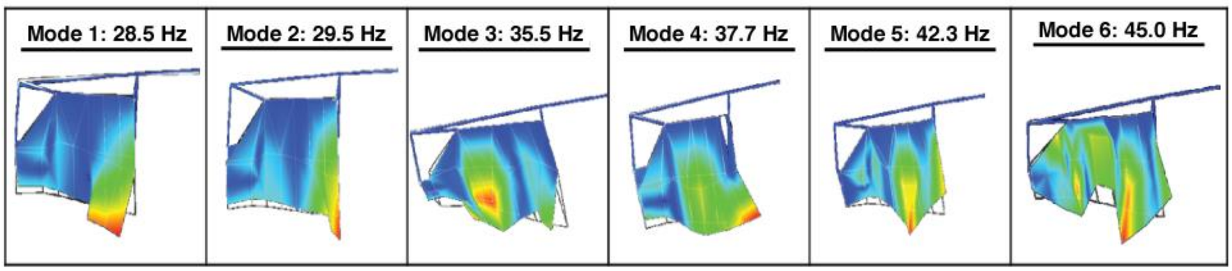


Figure 7. P3.2B GVT data for 30° deflection.

C. Flight Article Free-Free Ground Vibration Testing

The ACTE flight article free-free GVT was the third modal test conducted by NASA personnel at the NASA AFRC Flight Loads Laboratory (FLL) in March 2014. The test article for this GVT was the ACTE flight hardware for the right side flap before all of the flight instrumentation was installed. The ITS was the same design as what was tested for P3.2B. The test objectives were to measure the ACTE right flap structural frequencies, mode shapes, and damping data at the three critical deflections (0°, +15°, and +30°) with a free-free boundary condition. The three deflections identified served to bound the expected results and confirm the measured trend. The flight article free-free GVT objectives were as follows:

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.

Prior to performing the right flap free-free GVT, a weight and CG measurement of the flap was done. Figure 8 shows the GVT setup with the ACTE right flap in a free-free boundary condition which utilized an overhead soft suspension system made from a load cell and two custom bungees connected from the test article to the overhead crane in the FLL. On the test article, the two inner of the four shipping clevises along the flap spar were used as lifting points for the soft suspension system, and the two outer clevises were used to secure the right flap in the shipping crate for actuation and overnight securing. Excitation was provided by using a shaker supported by a small shaker stand and attached to the test article using a conventional stinger at five locations for the 0˚ configuration and at two of the five locations for the 15˚ and 30˚ configurations. Along with collecting typical accelerometer data, two non-contact systems (photogrammetry system and scanning laser doppler vibrometer) were used for a limited number of test cases across the TS as a research effort for evaluation in the acquisition of GVT data.

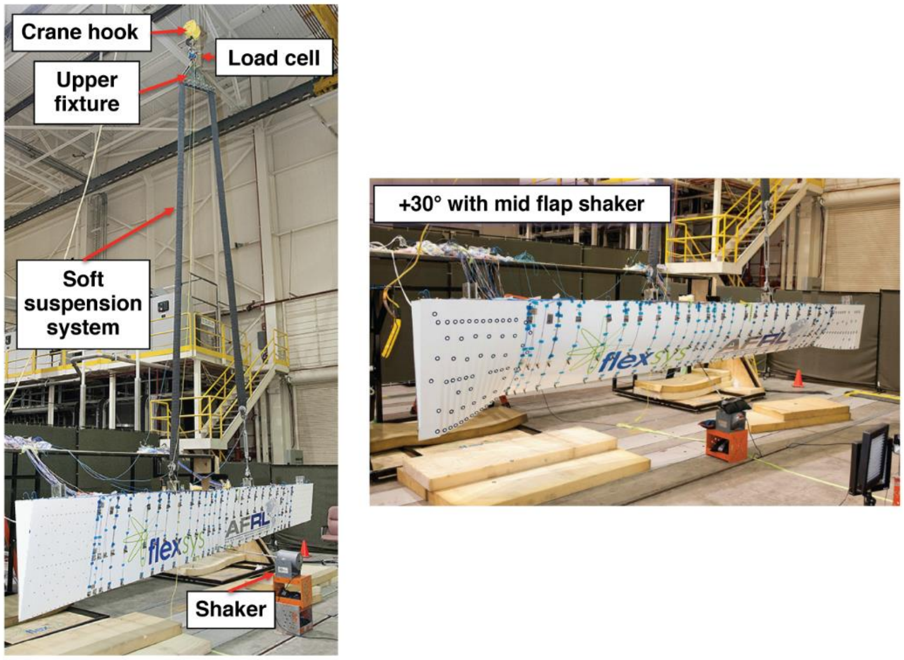


Figure 8. ACTE right flap free-free GVT setup.

The results from right flap free-free GVT at different flap deflections are shown in Fig. 9. After the GVT data were analyzed, the fourth GVT planned in the build-up testing approach, a “Mated SCRAT/ACTE GVT,” was deemed unnecessary to further refine the FEM.

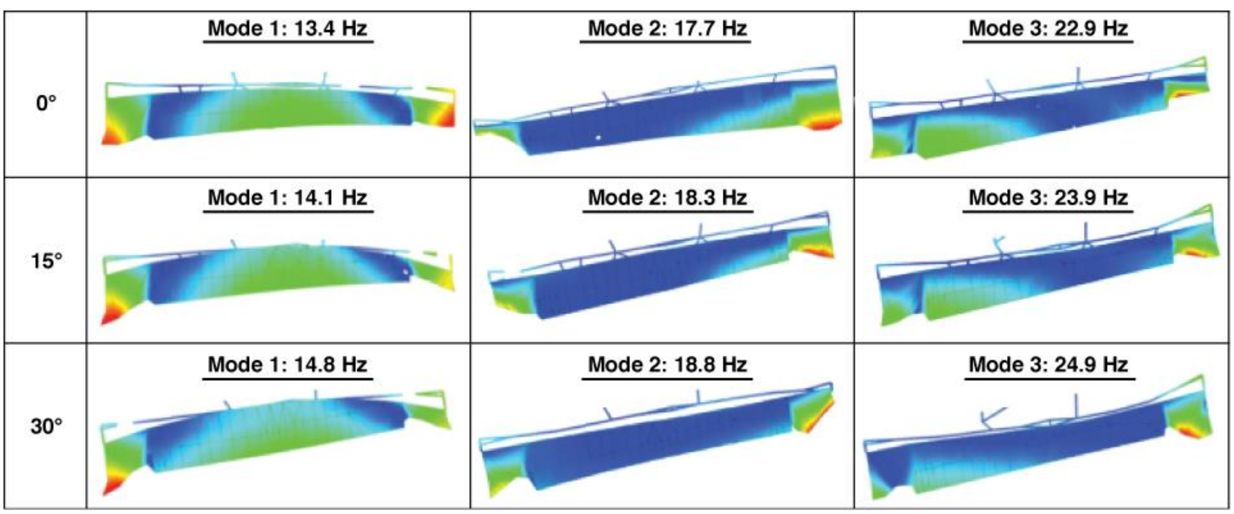


Figure 9. ACTE right flap GVT results at different deflections.

IV. Aeroelastic Analysis

When the Fowler flaps of the SCRAT aircraft were replaced by the ACTE flaps, the aircraft as well as the new flaps needed to be cleared for flutter within the ACTE flight envelope. Flutter is a subset of aeroelasticity which involves the interactive superposition of aerodynamic, elastic, and inertial forces on structures to produce an unstable oscillation that often results in structural failure. An extensive aeroelastic clearance process ensures the modified aircraft is free of flutter within the flight envelope. The flutter clearance process involves the combination of pre-flight flutter analysis and flight flutter testing. Pre-flight flutter analysis includes a FEM which was updated based on the

GVT results and an aero model based on the panel method. A detailed description for this process will be discussed in the following sections.

A. Model Correlation

A FEM was created for the ACTE flap using a typical combination of shell and beam elements. The model was built by FlexSys using ANSYS® eight node quadrilateral element for stress calculation, converted to four node quadrilateral element in Nastran™ format for modal analysis. The model contains 44,060 nodes and 66,300 elements as shown in Fig. 10. During the modeling of the ACTE flap, the biggest challenge was the modeling of the transition section due to the large deflections of the flexible structure. Since the modal analysis is linear, material properties for the transition section had to be linearized. Using the build-up approach mentioned above, the equivalent linear material properties for the transition section were obtained. The FEM was then correlated with the GVT results.

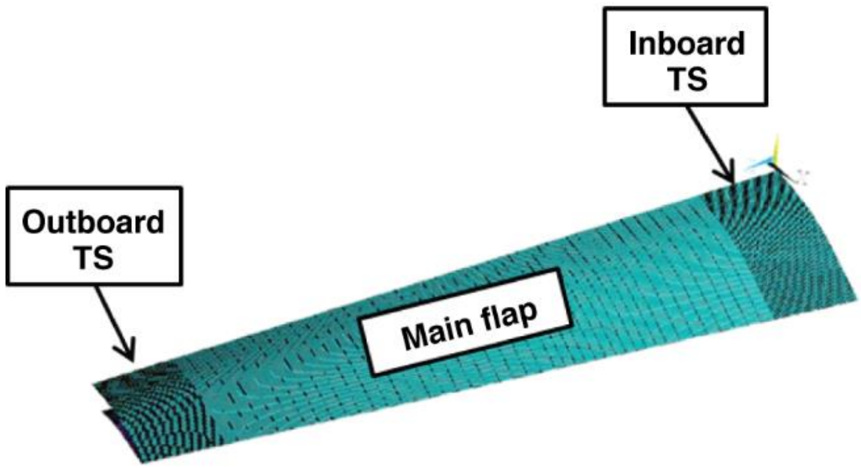


Figure 10. Finite element model of the full ACTE flap.

1. P3.2B Model Correlation

The Prototype 3.2B of the inboard transition section was the test article used for this GVT. A FEM extracted from the full ACTE flap model for model correlation is shown in Fig. 11. The P3.2B model contains 14,210 nodes and 22,724 elements. Figure 12 depicts the vibration mode shapes from a modal analysis using Nastran™. The natural frequencies of the first five elastic modes for various configurations are summarized in Table 2.

Table 2. FEM natural frequencies of P3.2B for different deflections.

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

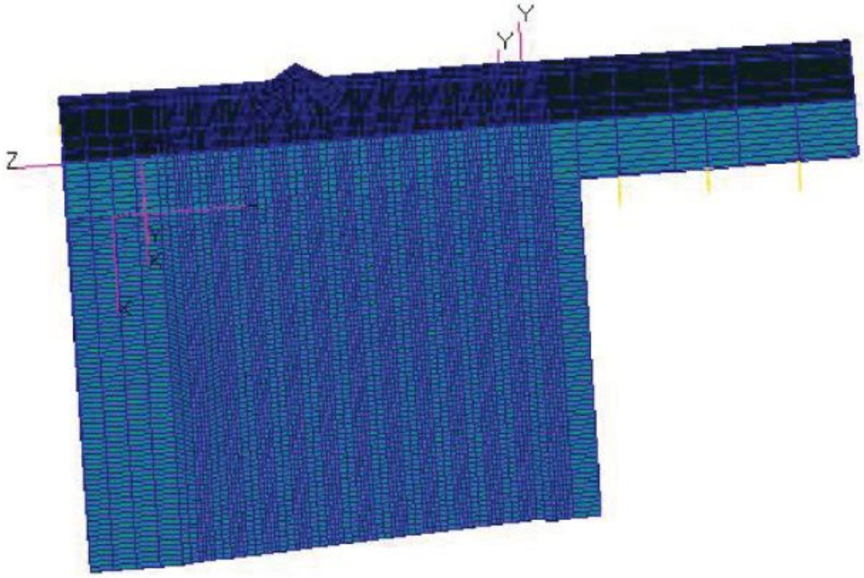


Figure 11. Finite element model of the Prototype 3.2B.

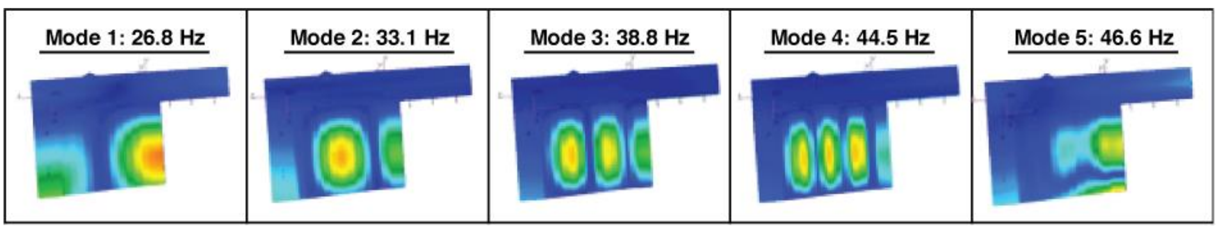


Figure 12. First five elastic modes from the 0° configuration for P3.2B FEM.

2. Flight Article Model Update

After the validation of the Prototype 3.2B was completed, the material properties used in the Prototype 3.2B were inserted into the full-flap FEM. Once again the final full-flap FEM was validated and updated using the full-flap GVT results. Figure 13 shows the vibration mode shapes for the 0° configuration. Natural frequencies for 0°, 15°, and 30° configurations are summarized in Table 3.

Table 3. FEM natural frequencies for different full ACTE flap configurations.

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

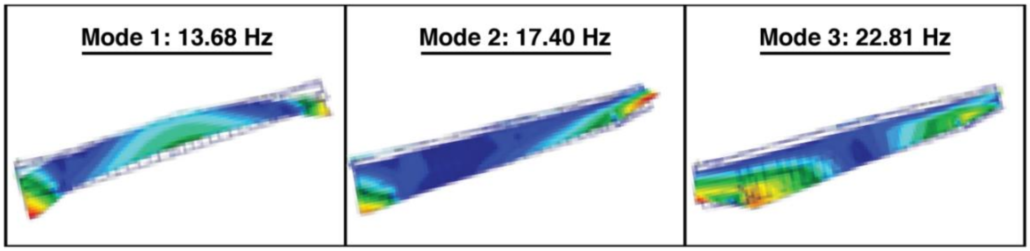


Figure 13. First three elastic modes from the 0° configuration for the full ACTE flap FEM.

3. Analysis versus Test

By comparing analysis results with the GVT results, the final flap model shows good correlation with the GVT data.[14] Frequency comparison between FEM results and the GVT data for 0°, 15°, and 30° configurations are summarized in Table 4.

Table 4. Frequency comparison between FEM and GVT results.

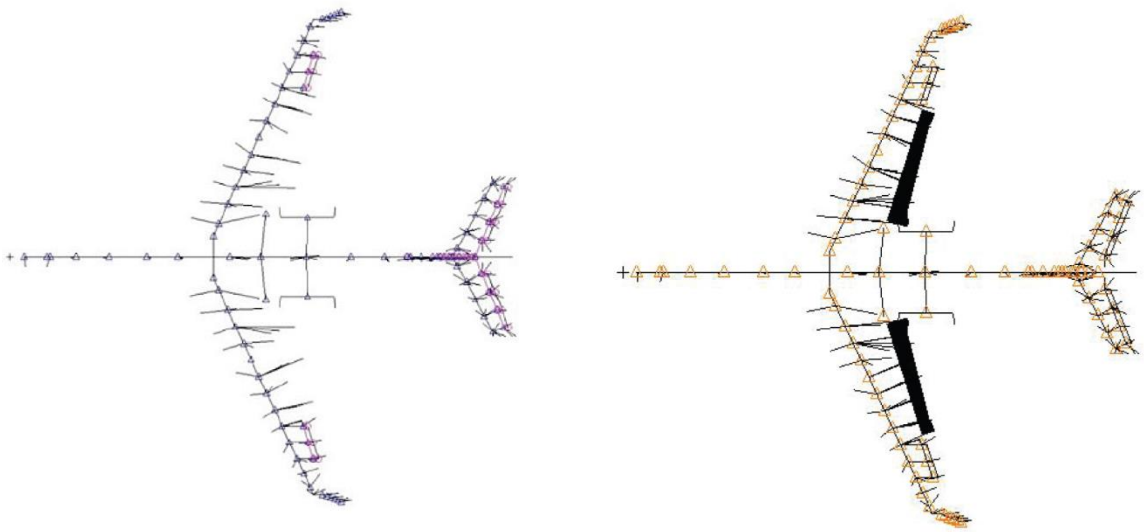
Mode	0° (Wing OML)			15° (Down)			30° (Down)		
	FEM (Hz)	GVT (Hz)	Delta	FEM (Hz)	GVT (Hz)	Delta	FEM (Hz)	GVT (Hz)	Delta
1	13.7	13.4	-2.2%	14.1	14.1	0.0%	14.9	14.8	-0.7%
2	17.4	17.7	1.7%	18.5	18.3	-1.1%	19.2	18.8	-2.1%
3	22.8	22.9	0.4%	23.8	23.9	0.4%	23.8	24.9	4.6%

B. Pre-flight Analytical Predictions

The pre-flight flutter analysis was used to identify the flutter characteristics of the combined system, establish broad trends over the flight envelope, and provide the guideline for planning the flutter test. Flutter computations involve structural modal analysis from which the frequencies and mode shapes are incorporated into the aerodynamic model for flutter analysis.

1. Structural Modal Analysis

The baseline SCRAT FEM was developed using a half GIII aircraft FEM obtained from GAC.[15] The SCRAT FEM is a stick model containing mainly beam elements. The structural modal analysis was performed using a FEM which was updated based on the GVT results. The ACTE flap models were then added to the stick model using Nastran™ CBUSH elements. Figure 14 depicts the FEM for the baseline SCRAT aircraft and the combined ACTE flaps. Typical vibration mode shapes from the modal analysis are shown in Fig. 15.



a) Baseline SCRAT FEM model. **b) SCRAT with ACTE flaps.**

Figure 14. SCRAT FEM with and without ACTE flaps.

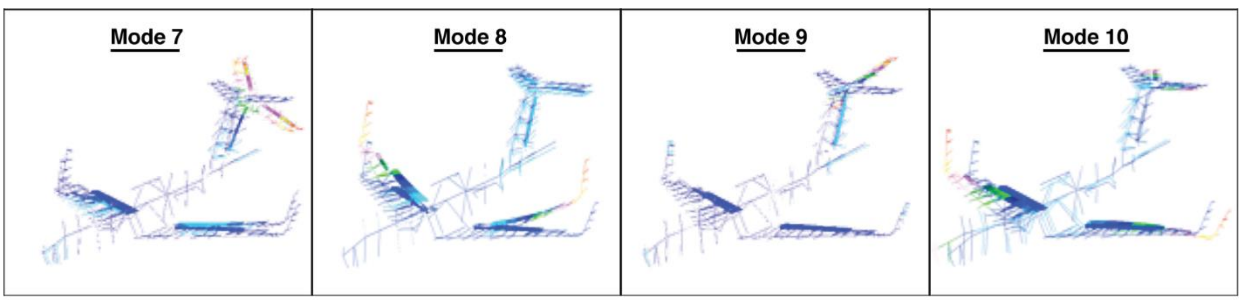


Figure 15. Typical vibration mode shapes for the SCRAT aircraft with ACTE flaps.

2. Flutter Analysis

Flutter analyses were performed using ZAERO (Zona Technology Inc., Scottsdale, Arizona)[16] matched point procedure. AFRC developed the baseline SCRAT aerodynamic model by obtaining a half aerodynamic model from GAC and updating it to reflect the full configuration to be flight-tested that included the ACTE flaps. This model contains 3021 flat panel elements as shown in Fig. 16. Flutter analyses were carried out for two fuel conditions, full fuel and empty fuel, with 0°, 30°, and -2° flap configurations. The calculated flutter speeds for different Mach numbers are summarized in Tables 5 and 6. A typical v-g plot and v-f plot are shown in Fig. 17.

Table 5. Predicted flutter boundary for different flap angles (empty fuel).

Flap angle	Mach = 0.6			Mach = 0.7			Mach = 0.8		
	Speed	**Frequency**	**Altitude**	**Speed**	**Frequency**	**Altitude**	**Speed**	**Frequency**	**Altitude**
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

Table 6. Predicted flutter boundary for different flap angles (full fuel).

Flap angle	Mach = 0.6			Mach = 0.7			Mach = 0.8		
	Speed	Frequency	Altitude	Speed	Frequency	Altitude	Speed	Frequency	Altitude
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

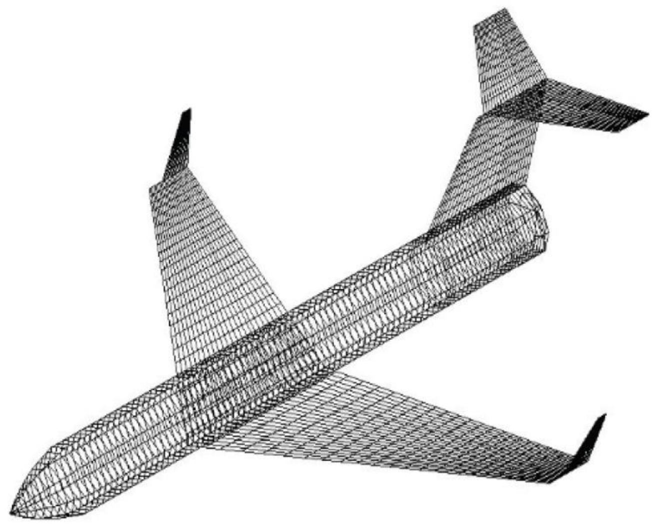
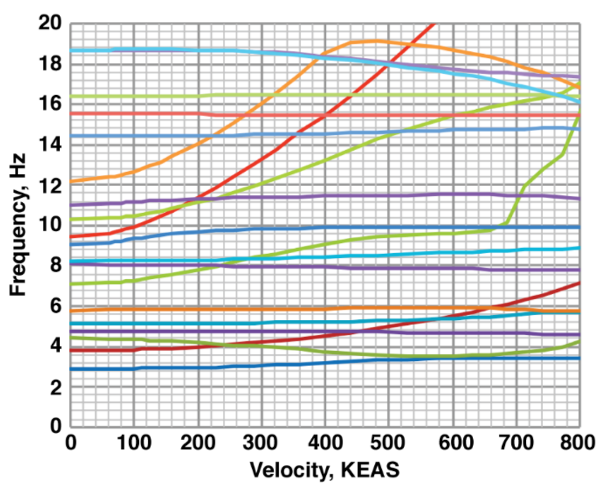
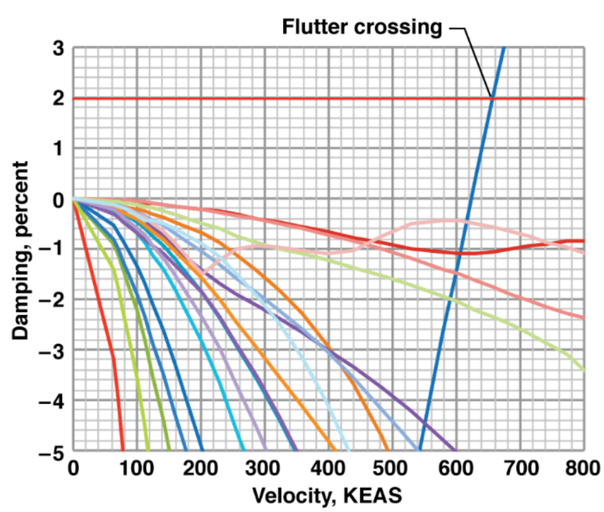


Figure 16. SCRAT aerodynamic model.





a) v-f plot. **b) v-g plot.**

Figure 17. Typical v-f and v-g plots.

V. Flight-Testing

Flight-testing of the ACTE flaps occurred from November of 2014 to April of 2015.[17] The ACTE flaps were deflected through their full operational range. The pre-flight analytical predictions and flight-test results are presented in this section. Analysis and flight-test results are compared for model validation purposes.

A. Pre-flight Analytical Predictions

The pre-flight analytical predictions were derived following the process described in the previous section. A set of predictions was developed for each deflection and was verified in the control room during flight-testing by comparing the flight-test results. These flight-test points were considered the anchor points since the flight-test results could be compared directly to analytical predictions. The ACTE flaps were also deflected to positions that were not analyzed. These flight-test points were considered spot checks since the flight-test results could only be used to verify trends between anchor points. Table 7 shows the results for the ACTE flap at 0° deflection for both empty and full fuel SCRAT configurations.

Table 7. Pre-flight analytical predictions.

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

B. Project Approach

The ACTE project employed a build-up approach to flight-testing that entailed clearing the ACTE flight envelope starting from low altitude and slow speed followed by high altitude and slow speed, thirdly by high altitude and high speed, and finally by low altitude and high speed in such a manner to increase the dynamic pressure and Mach number strategically through the envelope. The Mission Control Center (MCC) at AFRC was staffed to monitor mission critical, safety of test, and safety of flight parameters. A safety chase aircraft was required, and an on-board crew of three populated the SCRAT for all flights. A set of flight-test maneuvers was accomplished to validate stability and controls and aerodynamics models, structural analyses, and aeroelastic predictions at incremental speeds. Figure 18 shows the ACTE flight envelope for all flap deflections. The high speed/high altitude envelope provided the flight limits for the small flap deflections. The low speed/low altitude envelope shown provided the flight limits for the large flap deflections.

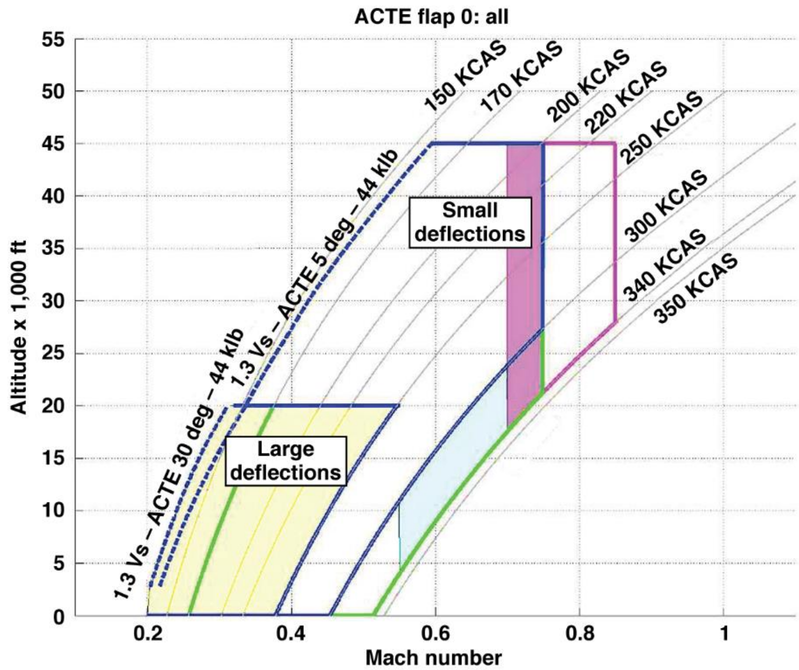


Figure 18. ACTE Flight Envelope.

C. Transition Section Results

The transition section was instrumented based on the preliminary modal analysis done on the ACTE flaps. The instrumentation installed on the ACTE right flap is shown in Fig. 19.

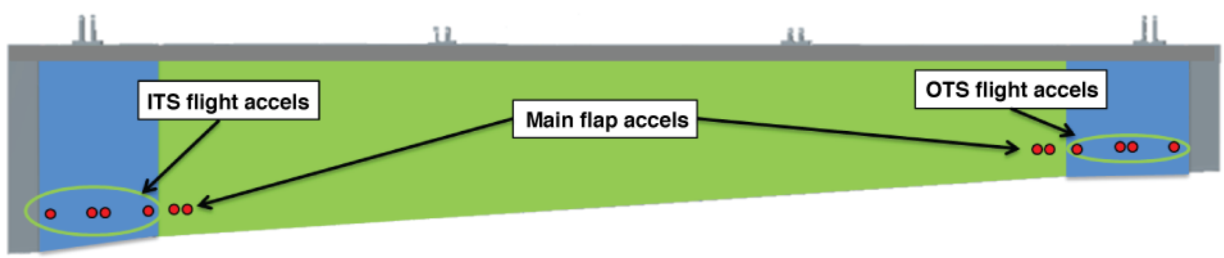


Figure 19. ACTE Right Flap Instrumentation.

The ACTE left flap has the mirrored version of the right side instrumentation suite. All accelerometers were monitored for the entire duration of flight-testing from the MCC. The Symvionics (Arcadia, California) InterActive Display Software (IADS®) was used in the MCC to monitor time-histories and calculate power spectral density (PSD) plots. The half power damping (HPD) method was applied to estimate the damping for all the modes observed.

Before take-off the transition sections were excited by manual taps from an aircraft crew member, and the response was measured. During flight-testing, response data provided by various maneuvers were used to estimate frequency and damping. Table 8 shows the response from the right and left side inboard and outboard TSs measured during the flight test for the 0° flap setting during one of the initial flights. The data shown were gathered at 10k ft altitude and Mach 0.46. The excitation was provided by light turbulence. Mode symmetry was evaluated by comparing the phase of the accelerometer signals post-flight.

Table 8. Right side transition section flight-test response for 0°.

		Left side flap		Right side flap	
Mode	**Description**	**Flight frequency (Hz)**	**Damping (%)**	**Flight frequency (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%

In addition, high frequency data were collected for the transition sections to investigate panel-type responses. The panel-type frequencies observed in the transition sections are shown in Table 9.

Table 9. High frequency response.

Transition section	Sensor	Frequency (Hz)
ITS	FL2006A	282.8
OTS	FL2016A	241.6
OTS	FL2016A	282.8

D. Analysis versus Test

The comparison between analytical predictions and test results for the right side transition sections deflected at 0° (wing OML) is shown in Table 10. The flight value was measured at the flight condition of Mach 0.75 and 21,200 ft, which equates to a dynamic pressure of 365 psf, the maximum dynamic pressure of the SCRAT/ACTE system. The maximum dynamic pressure condition is the worst case condition for this structural system. The comparison for the OTS frequencies show a good correlation between the analysis and flight test results. The ITS in-flight frequencies showed higher values than that of the analysis, indicating the analysis had some conservatism included.

Table 10. Transition section analysis/test comparison for 0°.

Description	Analytical empty fuel frequency (Hz)	Left side flight frequency (Hz)	Right side flight frequency (Hz)	Analytical full fuel frequency (Hz)
ACTE ITS symm	19.28	19.10	19.30	18.44
ACTE ITS anti	19.34	18.30	18.30	16.45
ACTE OTS symm	21.80	21.40	21.40	20.05
ACTE OTS anti	23.20	22.40	22.40	20.23

The high frequency responses showed similar comparisons. In addition, the OTS exhibited a lower frequency, but the frequency observed was still in line with the value produced by the analytical prediction. The comparison of the right side transition sections to the analytical value is shown in Table 11.

Table 11. High frequency response.

Sensor	Analysis	Flight
FL2006A	282.8	295.0
FL2016A	241.6	
FL2016A	282.8	

VI. Conclusions

The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) was able to successfully integrate two unique unconventional lifting surfaces into the airframe of a modified GIII aircraft to replace the existing Fowler flaps. Some non-linear modeling techniques were applied to the FEM, and a build-up testing approach was used to validate the FEM and show compliance with the 20% flutter margin requirement. In addition, pre-flight predictions were developed from this analysis and testing effort to assist in successful completion of validating the ACTE structure in flight. The analysis and testing results showed good correlation and demonstrated a successful modeling and validation effort despite the challenges presented.

Several different aspects of follow-on work are currently being discussed due to the accomplishments of this ACTE flight-testing campaign. These areas of work would expand the capability of the current ACTE flaps and the understanding of the adaptive compliant structure with continuous mold-line technologies. The follow-on work being developed would be to 1) perform additional ACTE flights to expand the ACTE flight envelope and demonstrate some twist capabilities for the ACTE structure, 2) evaluate the acoustic effects of the ACTE technology, and 3) integrate in-flight actuation for the ACTE flaps. NASA AFRC and their partners are excited for these opportunities to continue to explore this adaptive compliant wing technology.

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