Flutter Clearance for Captive Carry Flight Testing of the GOLauncher 1 Inert Test Article Mounted on C-20A Aircraft

CRASTE: June 27, 2018

Natalie Spivey[1], Shun-Fat Lung[2] & Robert Roglin[3]

([1]NASA-Armstrong Flight Research Center, Edwards AFB, CA;
[2]Jacobs Technology, Inc., Edwards AFB, CA;
[3]Generation Orbit Launch Services, Inc., Atlanta, GA)

Agenda

- **Presentation will discuss details of NASA Armstrong's flutter clearance airworthiness approach required to clear the GO1 Inert Test Article (GO1-ITA) for captive carry flights**

- **Flutter Clearance Airworthiness Approach**
- **UAVSAR & ITA Comparison**
- **ITA Finite Element Model Development**
- **C-20 + ITA Ground Vibration Test**
- **ITA Moment of Inertia Test**
- **Finite Element Model Update**
- **ITA *mini*-Ground Vibration Test Checkout**
- **Flutter Analysis**
- **Flight Instrumentation**
- **Captive Carry Flutter Flight Testing**

Flutter Clearance Airworthiness Approach

- **Objective: Demonstrate the aeroelastic airworthiness for flight testing of the C-20 in a captive carry configuration with GO's ITA**

- **Requirements: Numerous project requirements, but the main level 1 requirement that drove all the other dynamics related requirements and the flutter clearance work was…**
  – C-20 aircraft with the GO1-ITA installed shall maintain a 20% margin on the flutter boundary

- **Four major tasks for dynamics were executed for airworthiness approach**
  1. **Finite Element Model (FEM) Development**
     - Multiple ITA FEMs were created with increased complexity over the project life cycle
  2. **Ground Tests**
     - C-20 + ITA Ground Vibration Test (GVT) – July 2017
     - ITA Moment of Inertia (MOI) Test – Oct. 2017
     - ITA *mini*-GVT Checkout – Nov. 14, 2017
  3. **Flutter Analyses of C-20 + ITA**
     - Multiple C-20+ITA flutter analyses were performed over the project life cycle as complexity of the FEM increased and FEM was updated with GVT & later MOI data
  4. **Captive Carry Flutter Flight Testing (envelope clearance)**
     - Supported flight planning, developed control room displays & supported flights

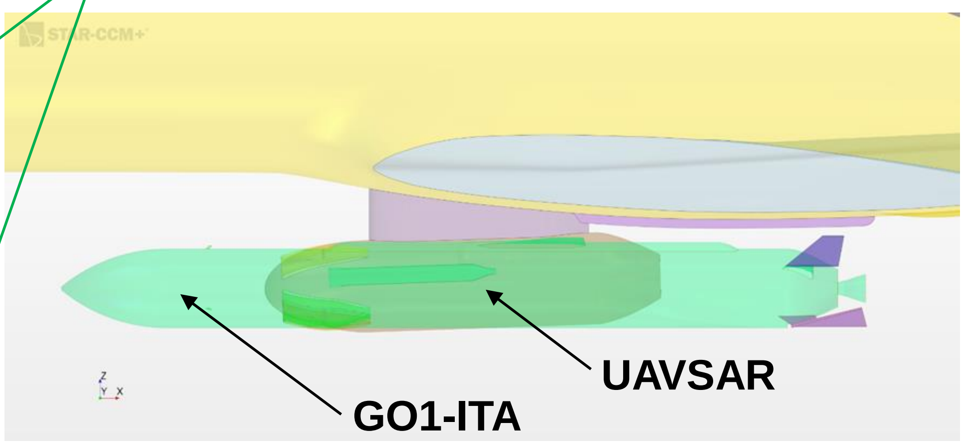
UAVSAR & ITA Comparison

- **C-20 aircraft was structurally modified in 2006 with a fuselage centerline pylon and MAU-12 ejector rack interface to serve as a test bed for a variety of flight research experiments**
  - Unmanned Aerial Vehicle Synthetic Aperture Radar (UAVSAR) pod has flown on centerline pylon for over 10 years
- **Armstrong desired to use past UAVSAR pod analyses as much as possible for comparison by similarity for the ITA clearance ⇒ to save cost & schedule**
  - ITA was 2x longer than UAVSAR pod & had significantly higher I_{YY} (pitch inertia) & I_{ZZ} (yaw inertia)
  - UAVSAR was not a good representation of the ITA

UAVSAR & ITA Comparison

	UAVSAR	ITA (initial values)	% Difference
Length (in.)	**129.6**	**262.8**	**-102.78%**
Diameter (in.)	30	25.9	13.67%
Mass (lbm)	1200	1200	0.0%
CG_X (in)	346.95	346.26	0.2%
CG_Y (in)	0.53	0.00	100.0%
CG_Z (in)	10.26	9.14	10.9%
I_XX (lb-in^2)	115,558	199,152	-72.3%
I_YY (lb-in^2)	**905,584**	**5,503,688**	**-507.7%**
I_ZZ (lb-in^2)	**899,509**	**5,486,416**	**-509.9%**

Significant Differences



ITA Finite Element Model Development

- **Multiple ITA FEMs were created with increasing complexity over the project life cycle**
  - Used existing pylon & torque box FEM from UAVSAR FEM

Pre-GVT

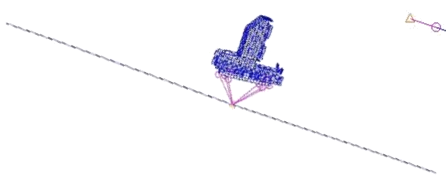
1) ITA <u>Stick FEM</u>
   - GO's ITA mass properties modeled with a lumped mass
2) ITA ANSYS detailed FEM converted to ITA Nastran <u>Equivalent Beam FEM</u>
3) ITA ANSYS detailed FEM converted to ITA Nastran <u>Detailed FEM</u>
   - Center body used solid elements

Post-GVT

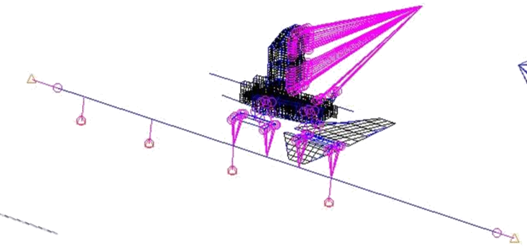
4) ITA ANSYS detailed FEM converted to ITA Nastran <u>Detailed FEM</u>
   - Center body used shell elements
5) ITA ANSYS full detailed FEM converted to ITA Nastran <u>Full Detailed FEM</u>
   - ITA FEM included wing, fins & body flaps
   - Center body used shell elements

ITA Wing structure only (no fins or body flaps) [items 2–4]

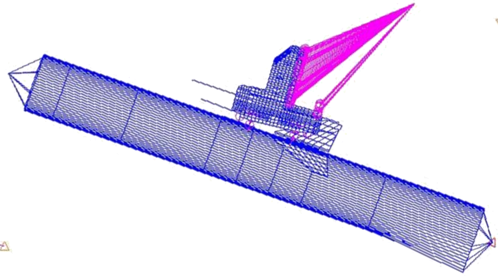
1) Stick FEM



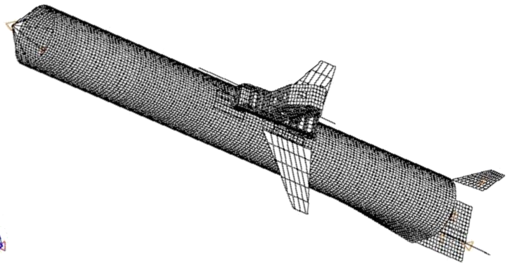
2) Equivalent FEM



3) & 4) Detailed FEM



5) Full Detailed FEM



C-20+ITA GVT

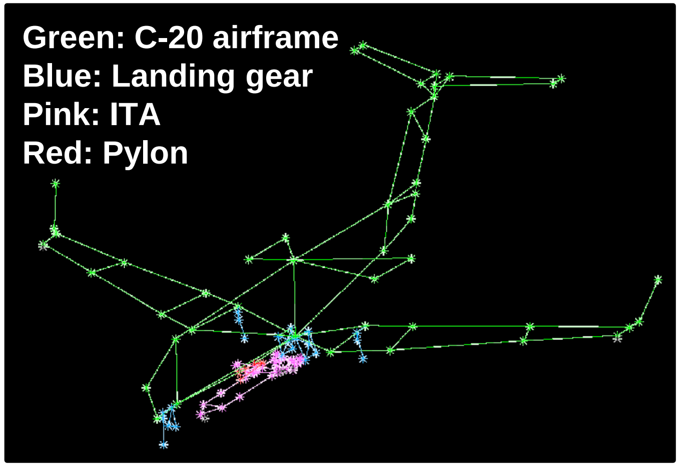
- **C-20 + ITA GVT conducted for July 5-13, 2017 on TN502 at Armstrong's 703 facility**
- **GVT required to update & validate the ITA FEM**
- **Objectives:**
  - Primary Objectives
    - Measure primary frequencies & mode shapes of the ITA rigid body modes (pitch, roll & yaw)
    - Measure first ITA flexible bending frequencies & mode shapes
  - Secondary Objectives
    - Measure ITA frequencies & mode shapes of the control surfaces
    - Measure lower (up to 20 Hz) C-20 frequencies & mode shapes with ITA installed
    - Measure C-20 main gear door frequencies with the doors extended and the ITA installed
- **Setup:**
  - C-20 with empty fuel configuration & on *soft* tires
  - GO's ITA installed in *near* final flight configuration
    - Body flaps & fins were not in the final flight configuration

C-20 + ITA GVT (July 2017)

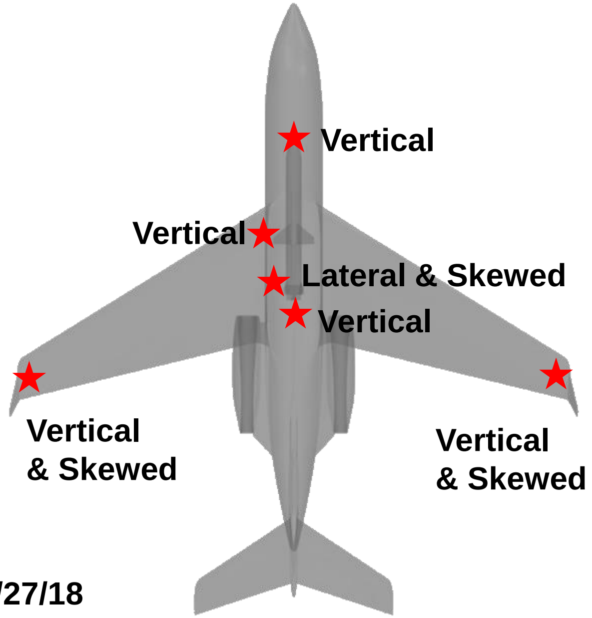
GVT – Accels & Excitation Locations

- **Total of 135 external accelerometer locations measuring ≈ 236 DOFs**
  - C-20: fuselage, wings, winglet, engines, T-tail, landing gear & gear doors
  - ITA: center body, wings, fins & body flap
  - Centerline pylon
- **Excitation used electromagnetic shaker(s) & impact hammer**
- **Excitation configurations:**
  - Config. A: 1 Shaker, ITA aft fuselage
  - Config. B: Impact hammer, ITA aft fuselage
  - Config. C: Impact hammer, C-20 Main Landing Gear Doors
  - Config. D: 3 Shakers, C-20 wingtips & ITA aft fuselage

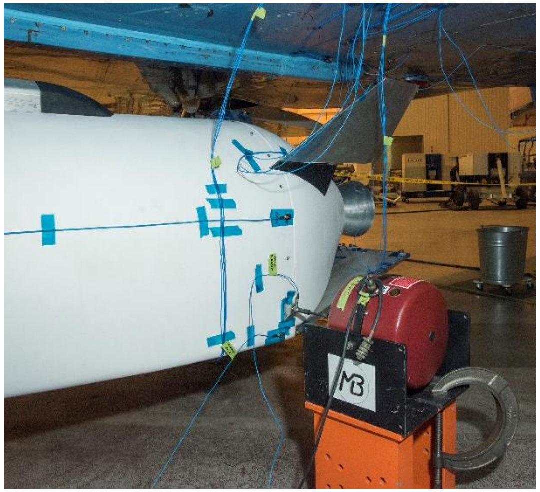
GVT Test Display Model



Excitation Locations



Config. A – ITA Shaker



Config. B – ITA Impact Hammer

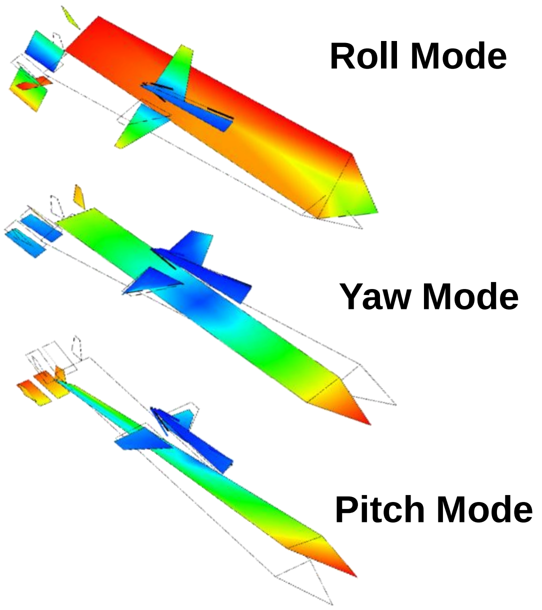
C-20 + ITA GVT – Summary

- **Total of 35 GVT test runs were acquired**
- **All primary & secondary test objectives were satisfied**
- **ITA GVT rigid body frequencies were very close together (within ≈ 1 Hz) & much lower than UAVSAR and yaw & pitch modes switched order**
  - ITA mode order & frequency ⇒ Roll, Yaw, Pitch
    - Two ITA roll modes measured: one clean ITA roll mode & one ITA roll mode coupled with C-20
  - UAVSAR mode order & frequency ⇒ Roll, Pitch, Yaw and much higher than ITA (not a good ITA representative)

C-20 + ITA GVT Modes Measured

Mode	Description
1	**ITA roll**
2	**ITA yaw**
3	**ITA pitch**
4	ITA right body flap coupled with slight C-20 mode
5	ITA left body flap coupled with slight C-20 mode
6	ITA wing antisymm
7	ITA fin antisymm In-Phase w/wing antisymm
8	ITA fin antisymm Out-Of-Phase w/wing antisymm
9	ITA wing symm
10	ITA vertical bending
11	ITA fin symm
12	ITA fin fwd/aft symm

ITA GVT: Rigid Body Modes



ITA Mass Property Testing at GO

- **ITA Moment of Inertia (MOI) testing conducted at GO in Oct. 2017**
  - GO developed a MOI test stand based on inverted pendulum method utilizing a spring assembly
  - Measured roll, yaw & pitch inertia (I_{XX}, I_{YY}, I_{ZZ}) & I_{XZ}
    - Suspected error in roll inertia, I_{XX} which also affected I_{XZ} so project used I_{XX} & I_{XZ} results from updated CAD

ITA MOI Testing

Final GO1-ITA Mass Properties at ITA CG

	Updated CAD Anchored to MOI test data	Measured from MOI test	Sim, Target Values	FEM w/ MOI results	Final Properties	Final Properties	Final Properties for Load Analysis
Weight (lbm)	1,206.7	1,206.8	1,200.0	1203.9	**1,206.8**	1,206.8	1,206.8
CG_X (in)	99.61	99.61	99.80	99.61	**99.61**	99.61	99.61
CG_Y (in)	-0.02	-0.21	0.00	-0.208	**-0.21**	-0.21	-0.21
CG_Z (in)	0.34	0.35	1.36	0.351	**0.35**	0.35	0.35

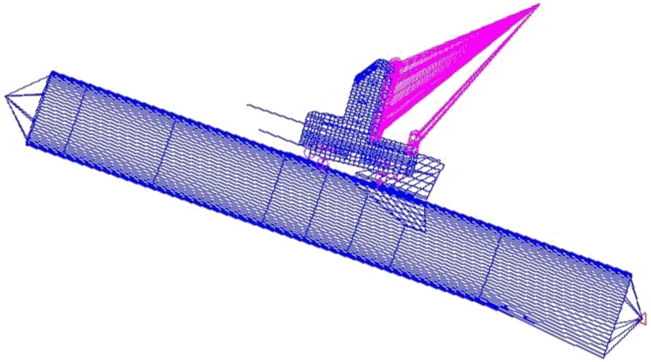
	Updated CAD Anchored to MOI test data (lbm-in^2)	Measured from MOI test (lbm-in^2)	Sim, Target Values (lbm-in^2)	FEM w/ MOI results (lbm-in^2)	Final Properties (lbm-in^2)	Final Properties (lbm-ft^2)	Final Properties for Load Analysis (slug-ft^2)
Ixx	204,318	TBD	199,152	179,900	**204,318**	1419	44
Iyy	5,738,382	5,754,859	5,503,680	5,770,000	**5,754,859**	39964	1242
Izz	5,718,991	5,747,653	5,486,400	5,740,000	**5,747,653**	39914	1241
Ixy	8,224	0	-259	-7,720	**8,224**	57	2
Ixz	62,080	TBD	17,136	71,100	**62,080**	431	13
Iyz	174	0	-14	-2,150	**174**	1	0

Project's Final mass properties from MOI test & CAD updated to match MOI test results

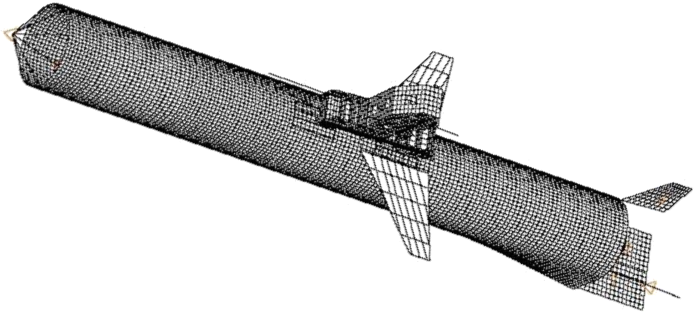
ITA FEM Update Process

- **After the GVT, the FEM model updating process began to match the GVT data and was done three different times with increased FEM complexity & FEM design variables**
  - 1st time: ITA <u>Detailed Post-GVT FEM</u> manually tuned the ITA's center body composite Young's Modulus for matching ITA rigid body modes only
  - 2nd time: ITA <u>Detailed Post-GVT FEM</u> manually tuned the ITA's center body composite Young's Modulus & connection stiffness for matching ITA rigid body modes only
  - 3rd time: ITA <u>Full Detailed Post-GVT FEM</u> (included fins & body flap) manually tuned to adjust the ITA's wings, fins and body flaps stiffness & mass properties
- **After MOI testing, the FEM was updated and manually tuned a final time to better match the ITA mass properties**

ITA Detailed FEM



ITA Full Detailed FEM



C-20+ITA *mini*-GVT Checkout

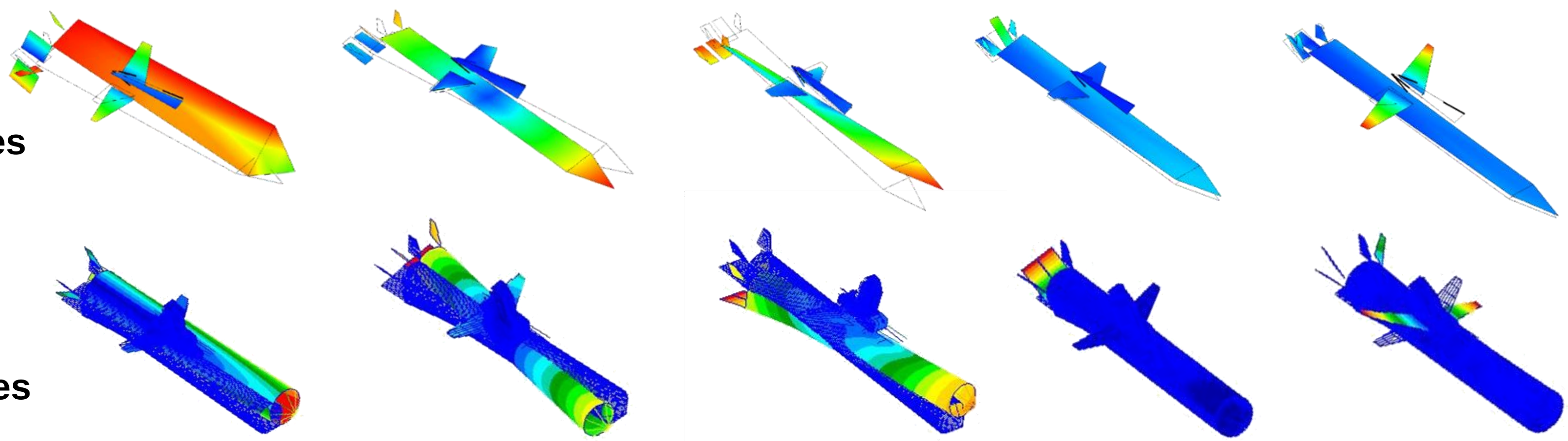
- **C-20 + ITA mini-GVT Checkout conducted for Nov. 14, 2017 on TN502 at 4801**
  - Required due to many changes to the ITA since the July GVT
  - Closed several RFAs & put to rest the MOI testing issue with roll inertia, I_{xx}
- **Objectives:** To measure ITA rigid body (roll, yaw & pitch) & ITA fins and body flaps frequencies & mode shapes
- **Setup:**
  - C-20 with empty fuel configuration & tires fully pressurized
  - ITA installed in <u>final</u> flight configuration
  - 24 triaxial accels installed on ITA, centerline pylon and pylon to aircraft connection
- **Results: All ITA rigid body & control surface frequencies increased**

C-20 + ITA *mini*-GVT Checkout (Nov. 14, 2017)

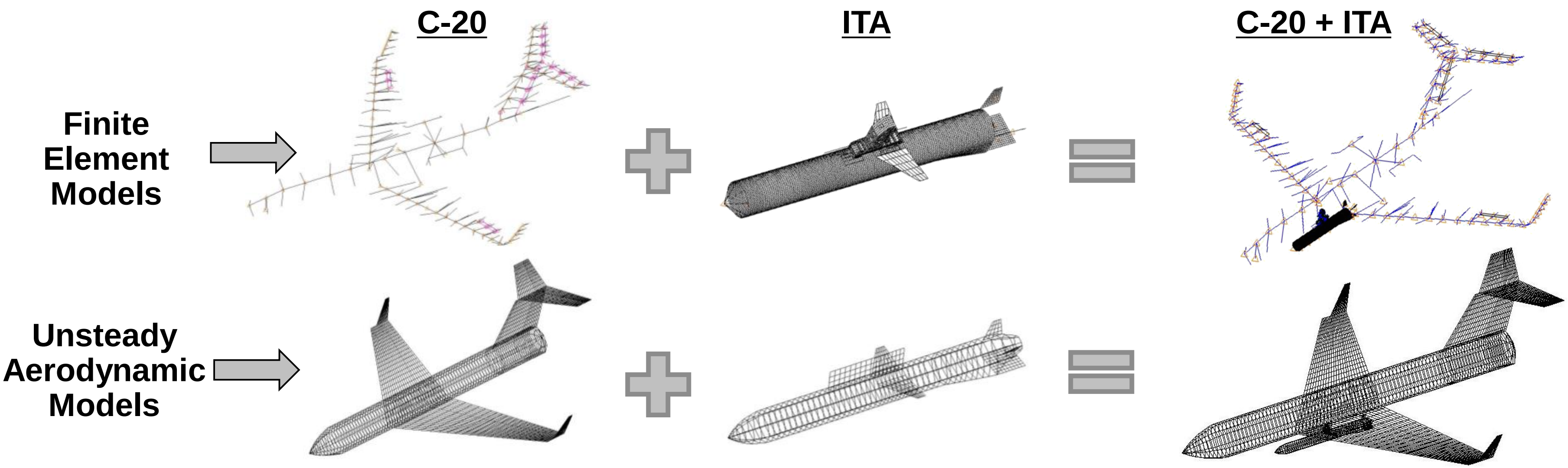
Comparison: GVTs vs. *Updated FEMs*

- *Mini*-GVT showed all ITA rigid body & control surface frequencies increased, so the final flutter analysis using the final updated FEM was deemed conservative due to the lower analytical frequencies

	ITA Roll	ITA Yaw	ITA Pitch	ITA Body Flap	ITA Wing ASYM
ITA GVT Mode Shapes					
ITA FEM Mode Shapes					

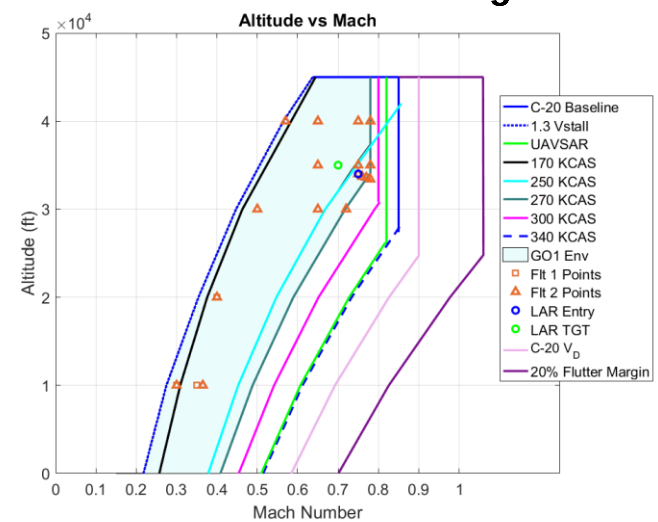


C-20+ ITA Flutter Analysis



- **ITA only flutter analysis was conducted & NO ITA flutter or divergence was found**
- **Match point flutter analysis done at 0.87M & 0.95M in ZAERO**
  - Analysis done with both aircraft heavy & light fuel
- **Flutter analysis assumed 0% damping - more conservative**
- **20% flutter margin requirement was met with ITA installed**
  - Flutter margin & flutter mechanism details are Gulfstream Aerospace Corporation proprietary
  - Final ITA FEM update did not change the flutter results after GVT
- **ITA slightly changed the typical C-20 flutter mechanism, but ITA roll modal participation factor was low**
  - Past NASA experiments have not changed the C-20 flutter mechanism
  - External stores/pods normally have higher frequencies like UAVSAR frequencies

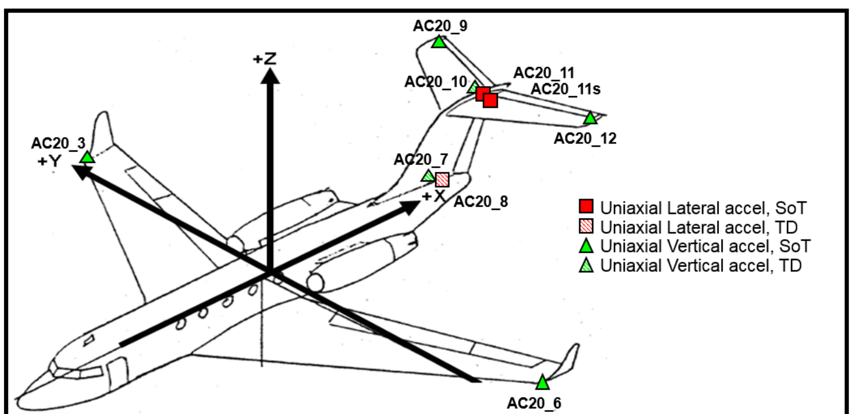
Flight Envelopes with 20% Flutter Margin



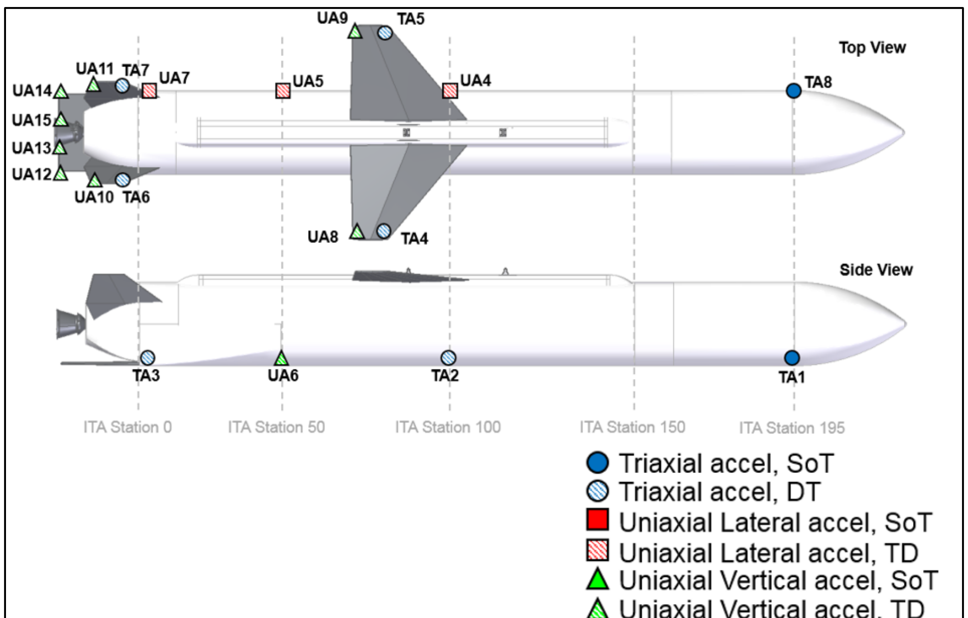
Dynamics Flight Instrumentation

- **C-20 & ITA accelerometers were telemetered from ITA to Armstrong's control room**
  - ITA's instrumentation system provided signal conditioning for both C-20 & ITA accels
- **After Combined System Test (CST) & prior to 1st flight some of the Safety of Test (SoT) ITA accelerometers were changed**
  - ITA accels showed little amplitude response during CST due to accel type & resolution (10 mV/g, ±500g's)
  - Replaced ITA nose accels with 2 higher resolution triaxial accels, PCB T356A16 (100 mV/g, ±50 g's)
- **C-20 & ITA accels were either Safety of Test (SoT) Go/No-Go or Technically Desired (TD) parameters during envelope clearance flights. All SoT accels had backups**
  - C-20: 9 uniaxial accels, 6 SoT & 3 TD parameters
  - ITA: 8 triaxial accels & 12 uniaxial accels, 2 SoT & 20 TD parameters
  - Pylon: No accels

C-20 Accels



ITA Accels



Dynamics Flight Test Approach & Control Room Operations

- **Build-up approach was used for envelope expansion**
  - Dynamics Maneuvers: Steady-state and Raps (not done above 250 KCAS)
- **Flight accels used to assess C-20 & ITA aeroelastic characteristics**
- **Dynamics control room staffing ⇒ Required minimum of two, desired four**
- **Control room operations:**
  - Conducted steady-state maneuver, dynamics evaluated data quality then gave clearance to next test point
    - Dynamics 2 & 3: *Conducted IADS time-domain analysis to estimated frequencies & damping (note: analysis failed/could not be computed due to the TM/packet dropouts)*
  - Conducted raps (pitch, roll & yaw), dynamics evaluated data quality then gave clearance to next test point
    - Dynamics 2 & 3: Conducted IADS frequency-domain analysis to estimate frequencies & damping
- **After 1st flight control room operations slightly changed**

Initial Plan

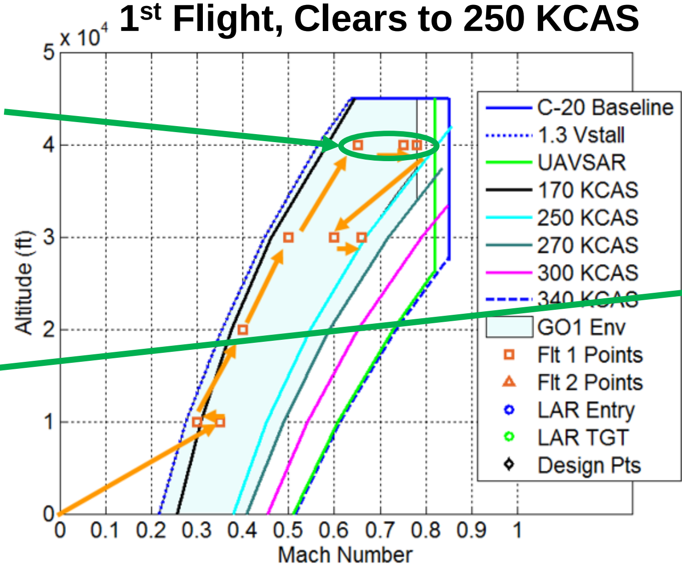
1st Flight: Steady-state & Raps

- 40k ft, 0.65M (116 psf)
- 40k ft, 0.75M (155 psf)
- 40k ft, 0.82M (185 psf)

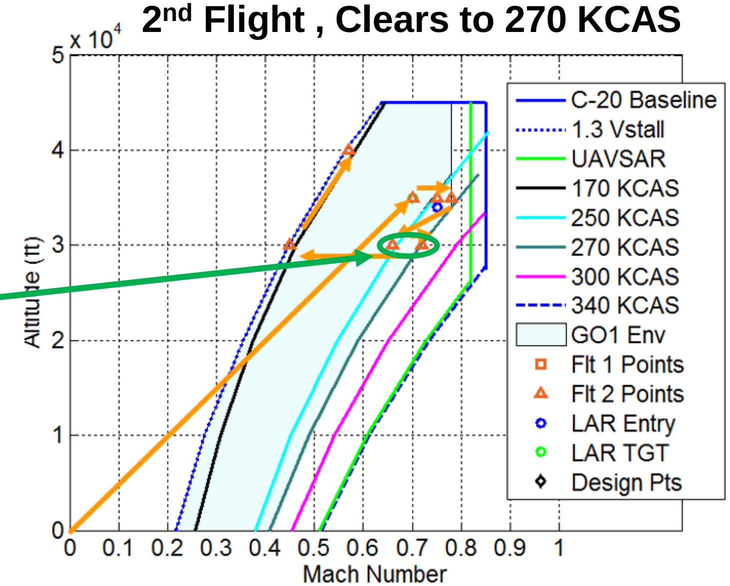
2nd Flight: Steady-state only

- 30k ft, 0.66M (192 psf)
- 30k ft, 0.72M (228 psf)

1st Flight, Clears to 250 KCAS

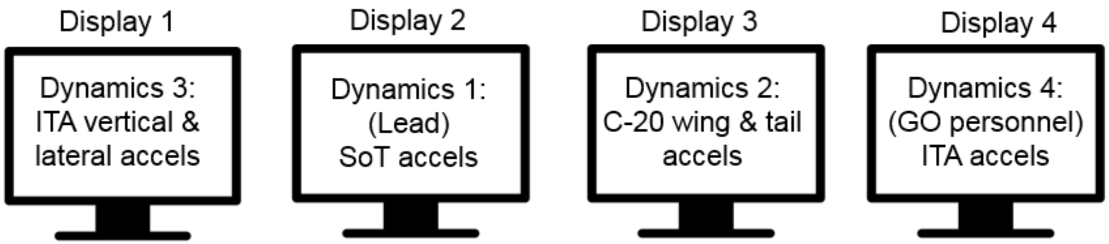


2nd Flight , Clears to 270 KCAS



Dynamics Control Room Responsibilities

- Developed control room displays using IADS to monitor real-time C-20 + ITA aeroelastic responses for envelope expansion flights
- Dynamics had 4 displays available in the control room



Dynamics Control Room Team

Dynamics 1 (Dynamics Lead) Responsibilities:
- Monitor all C-20 & ITA Safety of Test accels
- Monitor for diverging oscillations
- Clears test points
- Logs dynamics event markers

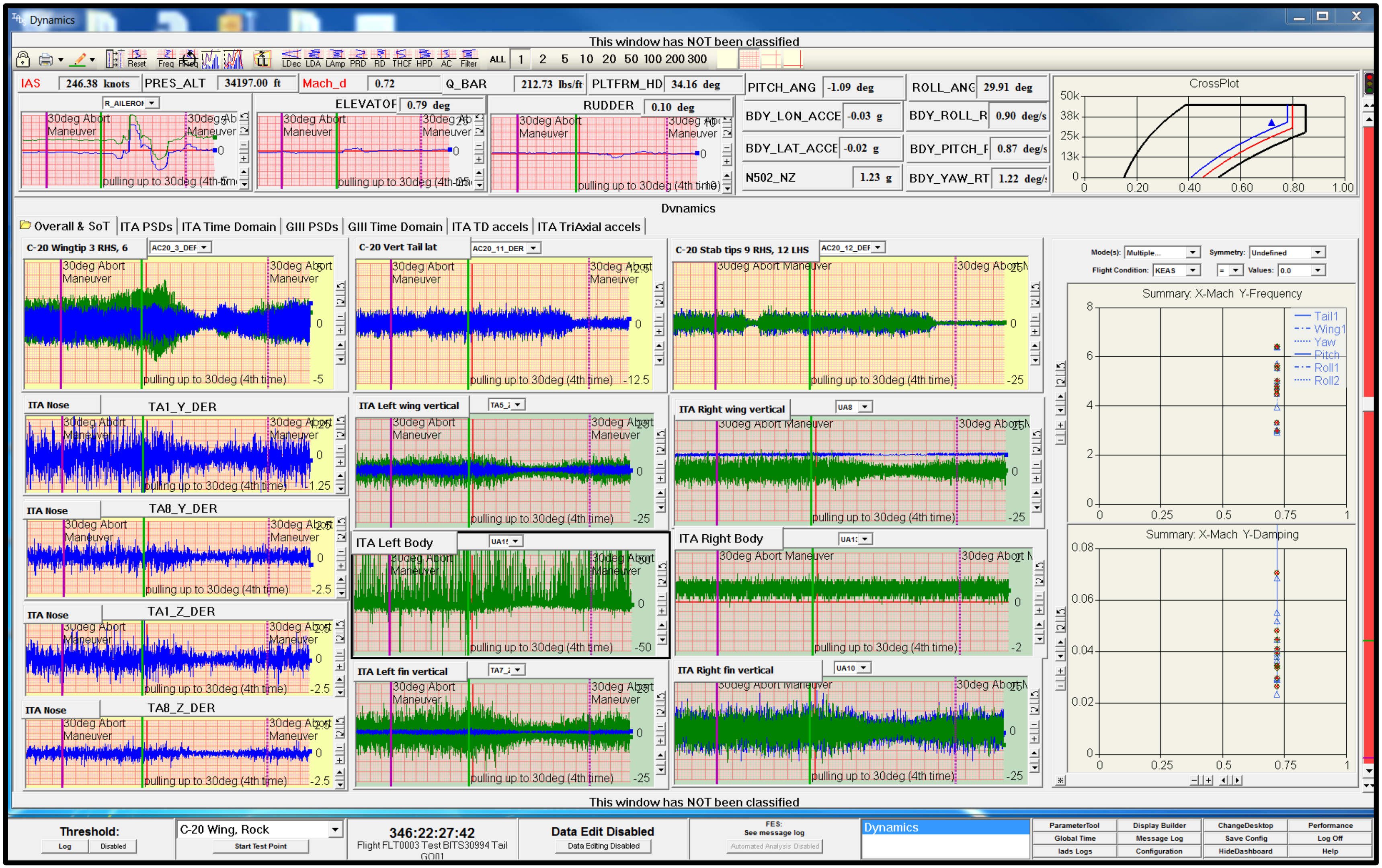
Dynamics 2 Responsibilities:
- C-20 wing & tail accels
- Switches between tabs to conduct time & frequency domain analyses to estimate frequencies & damping then log values

Dynamics 3 Responsibilities:
- ITA vertical & lateral accels
- Switches between tabs to conduct time & frequency domain analyses to estimate frequencies & damping then log values

Dynamics 4 Responsibilities:
- ITA accels

Dynamics Control Room – Display Example

- **Dynamics 1 (Lead): Monitored all Safety of Test accels using 1st tab *"Overall & SoT"***
  - Maneuver shown: 30° Flight Angle Launch Abort Release maneuver



C-20 + ITA Captive Carry Flight Testing

- **Dynamics Observations after 1st flight**
  - Flt #1 evaluated modal characteristics during steady-state maneuvers only (highest Qbar≈114 psf), no raps conducted before RTB was called
  - Steady-state maneuvers provided enough broadband excitation to excite both the aircraft & ITA modes of interest (very nice, unexpected)
    - Dynamics evaluated data quality then gave clearance to next test point, then conduced IADS frequency-domain analysis to estimate frequencies & damping
      - Frequencies & Damping followed expected trends
  - IADS Time-domain Random Decrement (RD) + Time History Curve Fit (THCF) analysis failed/could not be computed due to the TM/packet dropouts

- **Dynamics Go Forward Plan for 2nd flight**
  - Dynamics-continued to evaluate frequencies & damping with PSDs from steady-state maneuvers as higher dynamic pressures were cleared
    - Frequencies & damping were evaluated
      - In flight ⇒ Frequencies & damping followed expected trends, so dynamics eliminated rap maneuvers and ITA captive carry flight envelope was cleared

- **Dynamics 3rd flight**
  - Monitored accels during the ITA launch abort release maneuver starting with a 15° pitch attitude and the desired 30° pitch attitude

Structural Dynamics Conclusion

- **ITA GVT rigid body frequencies were close together (within ≈ 1 Hz) & much lower than UAVSAR**
- ***Mini*-GVT showed an increase in the ITA rigid body & control surface frequencies for the final ITA flight configuration which was good for flutter**
- **Final flutter analysis using FEM updated with MOI data showed adequate flutter margin for flight testing**
- **A build-up approach was used for envelope expansion flights & dynamics monitored C-20 & ITA accelerometers**
  - Dynamics maneuvers ended up being only steady-state test points (no raps)
- **ITA captive carry flight envelope was cleared with no aeroelastic issues**