NASA Armstrong's Structural Dynamics Airworthiness Processes for Aircraft

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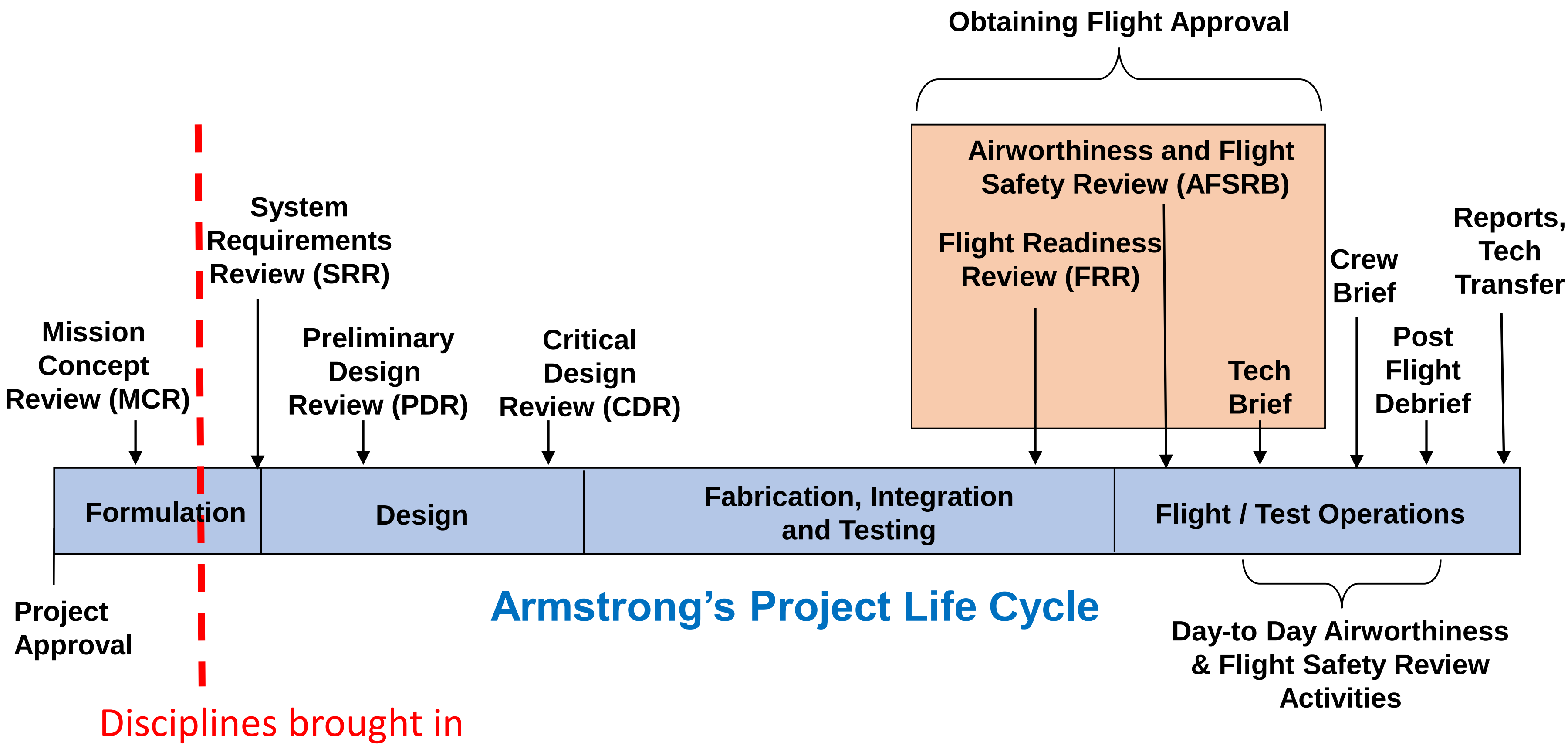
Outline

- NASA Armstrong's System Engineering Flow
  - Requirements
  - Project Hazards & Risks
- Structural Dynamics Guidance Documents
- Aeroelastic Instabilities for Aircraft
- Flutter Clearance Approach
- Airworthiness Process
  - FEM Development
  - Ground Testing
  - Flutter Analyses
  - Flight Flutter Testing
- Summary

- Airworthiness and Flight Safety Reviews
  - "The Airworthiness and Flight Safety Review Board (AFSRB) is tasked with performing certain review processes in order to ensure the flight safety of all projects conducted at Armstrong Flight Research Center."

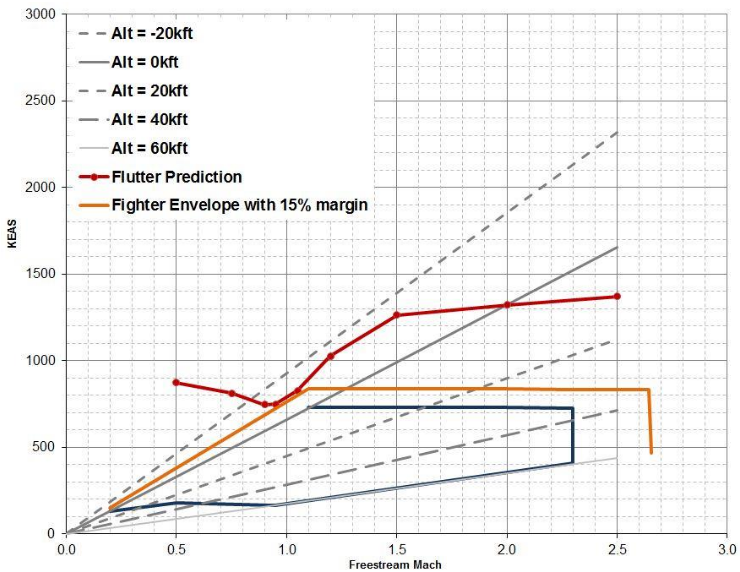


Requirements - Minimum Margins

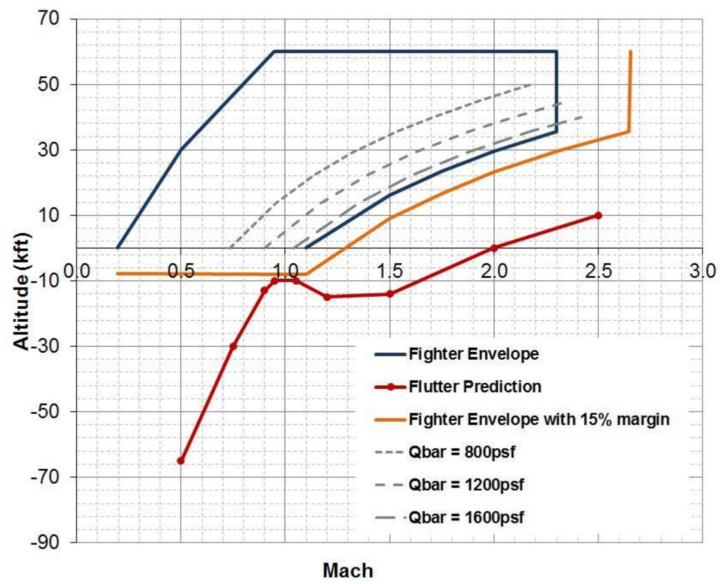
- Goal: Demonstrate the aeroelastic airworthiness of an aircraft / flight test article to be cleared for flight testing
  - Perform minimum effort required for airworthiness which depends on project's accepted risk level

- Requirement(s)
  - Minimum flutter margin for civil (FAA) & military (DOD) aircraft is now 15% on equivalent airspeed and Mach number
    - NOTE: NASA space vehicles require 32% flutter margin on dynamic pressure which is approximately the same as 15% margin on aircraft equivalent airspeed (1.3225 = 1.152)
  - Minimum gain margin of 8 Db & 60 degree phase margin on each feedback loop of the flight control system for prevention of any aeroservoelastic instability

Equivalent Airspeed vs. Mach Number



Altitude vs. Mach Number



Armstrong's Hazard Management Process

- Utilizes a continuous Hazard Management process throughout the project life cycle as outlined in DCP-S-002 (internal procedures) in compliance with NASA Safety Manual NPR 8715.3

- Project team holds System Safety Working Groups (SSWG) to works together to:
  - Identify hazards
  - Evaluate hazards for cause and effect
  - Score hazards for severity (human safety & loss of asset/mission) and probability
  - Identify mitigations to reduce the probability of occurrence

- Hazard Action Matrix (HAM) Scorecard

HAM - Human Safety

	Probability [Pr] Estimations				
Injury Severity Classifications	A: Expected to occur ($Pr > 10^{-1}$)	B: Probable to occur ($10^{-1} \geq Pr > 10^{-2}$)	C: Likely to occur ($10^{-2} \geq Pr > 10^{-3}$)	D: Unlikely to occur ($10^{-3} \geq Pr > 10^{-6}$)	E: Improbable to occur ($10^{-6} \geq Pr$)
I: Catastrophic					
II: Critical					
III: Minor					
IV: Negligible					

HAM – Loss of Asset / Mission

	Probability [Pr] Estimations				
Asset/Mission Severity classification	A: Expected to occur ($Pr > 10^{-1}$)	B: Probable to occur ($10^{-1} \geq Pr > 10^{-2}$)	C: Likely to occur ($10^{-2} \geq Pr > 10^{-3}$)	D: Unlikely to occur ($10^{-3} \geq Pr > 10^{-6}$)	E: Improbable to occur ($10^{-6} \geq Pr$)
I: Catastrophic					
II: Critical					
III: Minor					
IV: Negligible					

Armstrong’s Risk Management Process

- Risk management process is based on Continuous Risk Management (CRM) and Risk-Informed Decision Making (RDM) and evaluated throughout the project life cycle

- Projects do a Risk Management Plan (RMP) which complies to NASA Agency / Armstrong Center risk policies & guidance (NPR 7120.8 & NPR 8000.4A)

- Project team holds risk meetings to works together on:
  - Identify programmatic risks
    - Technical performance
    - Cost
    - Schedule
  - Evaluate risks for cause and effect
  - Generate new mitigations
  - Develop mitigation strategies to manage risks
  - Continue to evaluate newly identified programmatic risks
  - Evaluate and score risks using likelihood & consequence scorecard criteria

Structural Dynamics Guidance Documents

- Structural dynamics engineers use the following guidelines, handbooks & standards for aircraft / flight test article airworthiness assessments

Document Title / No.	Applicability
G-7123.1-001, AFRC Aircraft Structural Safety of Flight Guidelines	Flutter Margin, GVT, FE Model update
AFFTC-TIH-90-001, Structures Flight Test Handbook	**Flutter Margin, GVT, FE Model update**
NASA-STD-5002, Load Analyses of Spacecraft and Payloads	GVT, FE Model update
NASA-STD-7009, Standard for Models and Simulation	FE Modeling
MIL-A-8870C, Airplane Strength and Rigidity Vibration, Flutter and Divergence	**Flutter Margin**
MIL-STD-1540C Section 6.2.10, Test Requirements for Launch, Upper-Stage, & Space Vehicles	**FE Modeling**
FAR Part 25.629-1B, Aeroelastic Stability Substantiation of Transport Category Airplanes	**Flutter Margin, GVT, FE Model update**
FAR Part 23.629-1B - Means of Compliance with Title 14 CFR, Part 23, 23.629, Flutter	Flutter Margin, GVT, FE Model update
DOP – R – 601, Structural Ground Test Development & Execution	GVT
DCP – R – 602, Flight Loads Lab Configuration Management	
DCP – R – 603, Flight Loads Laboratory Operations Requirements Document	
DOP – R – 604, Flight Loads Laboratory Thermal-Structural Ground Test Hazard Analysis	
DCP – R – 064, Lifting Operations, Devices, & Equipment	
DOP – R – 007, Project Chief Engineer’s Handbook	Reviews

Aeroelastic Instabilities for Aircraft

- Aeroelastic instabilities common to aircraft
  - Classical Flutter
  - Divergence
  - Limit Cycle Oscillation (LCO)
  - Body Freedom Flutter
  - Whirl Flutter
  - Stall Flutter
  - Aeroservoelastic (ASE) Instability
  - Buzz
  - Panel Flutter
  - Cavity Resonance

Aerostructures Test Wing, Classical Flutter

- Identify the most likely type(s) of instability to be encountered in flight
  - If no supersonic flight then several instabilities are automatically eliminated as a concerns
  - Be wary of any others instabilities that might have been overlooked
  - Expect the Unexpected

Flutter Clearance Approach

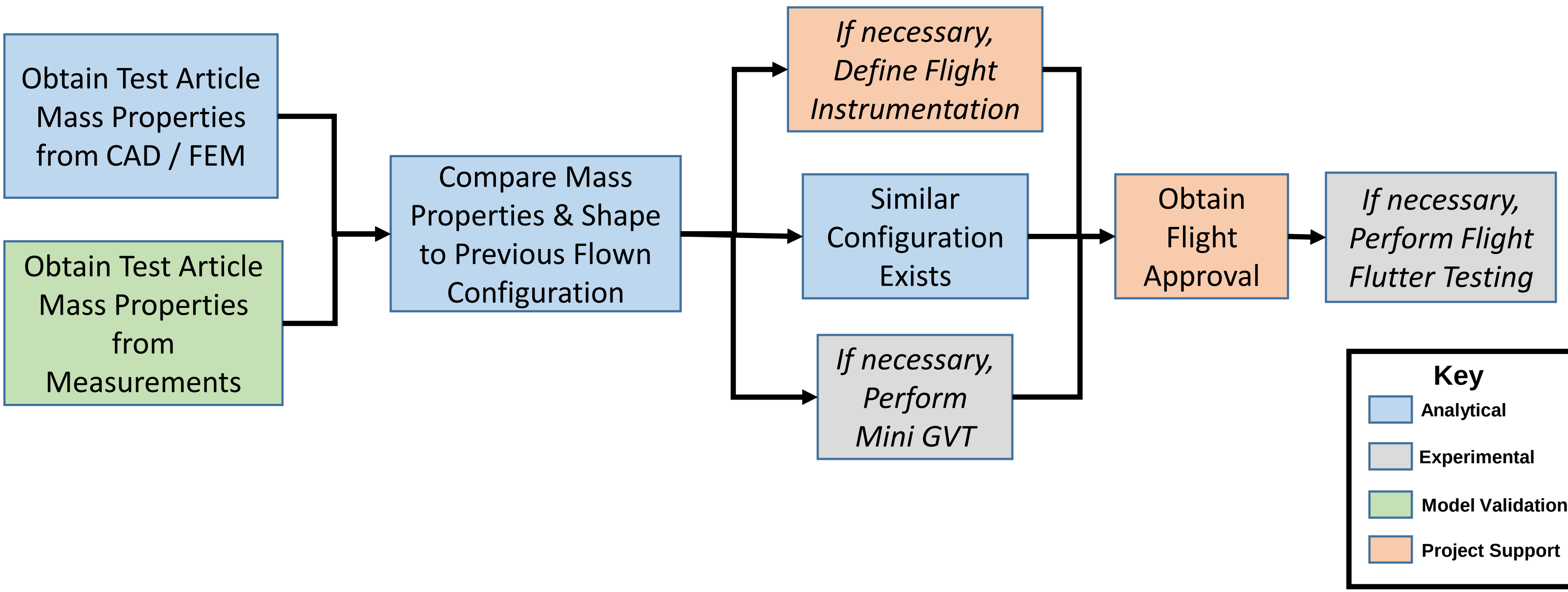
- Step #1: Gather historical aeroelastic information (stiffness and mass distributions, geometry) pertaining to the aircraft / test article
  - Expect airframe manufacturers to be reluctant to provide information
  - Previous FEM, GVTs, flutter analyses and flight flutter test results will be very useful for further flutter evaluation

- Step #2: Choose which flutter clearance approach is appropriate to show airworthiness of the aircraft / test article
  - Any of the following three may be an appropriate Flutter Clearance Approach to follow:
    1) **Clearance by aeroelastic similarity**
    2) **Clearance by analytical parametric investigation or flutter sensitivity study**
    3) **Clearance by flutter analysis, GVT, and flight flutter / ASE test**
  - Perform minimum effort required for airworthiness which depends on project's accepted risks

- Step #3: Perform flight flutter testing
  - Acquire flight test to correlate / validate aeroelastic mode
  - Full airworthiness demonstrated when models are correlated to flight test data

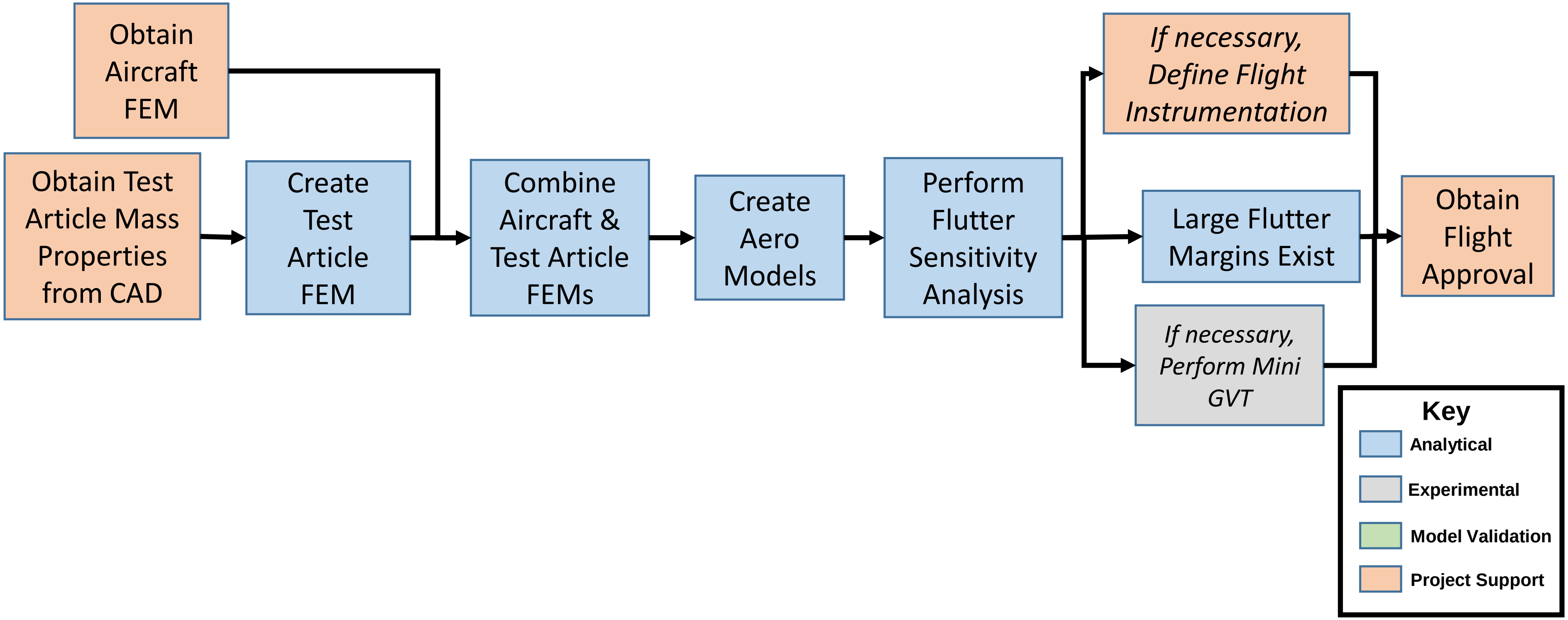
Flutter Clearance Approach #1
By Aeroelastic Similarity

- Flutter clearance by aeroelastic similarity
  - Minimum effort & very low cost approach
  - Similar mass & stiffness distributions and unsteady aerodynamic forces as previous flown and cleared configuration
  - Often used for new external stores
    - When stores are carried on same pylon at same aircraft location
    - Usually, external stores are quite stiff & treated as rigid-bodies attached to a flexible pylon
    - Shape, weight, CG location and inertias from CAD or measurements of both the old and new stores may be sufficient for comparison



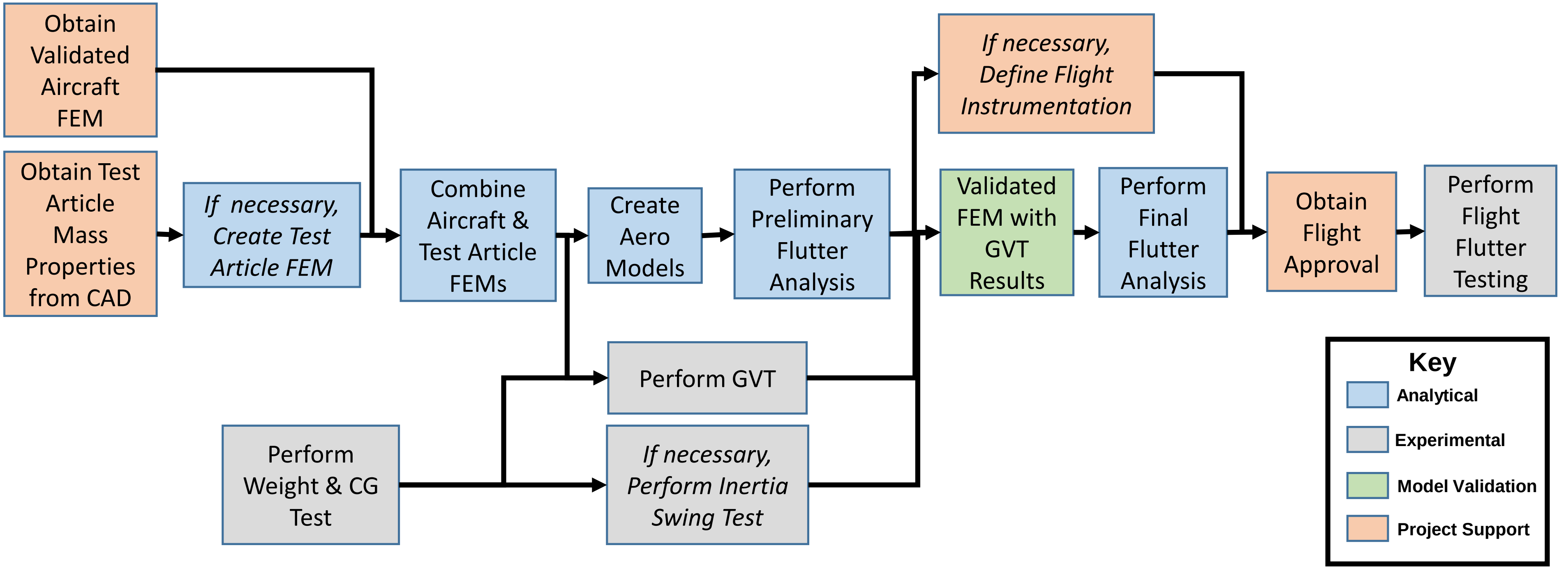
Flutter Clearance Approach #2 By Flutter Sensitivity Study

- Flutter clearance by analytical parametric investigation or flutter sensitivity study
  - When uncertainties in FEM parameters exist, a flutter sensitivity study can capture all possible variable combinations
    - Vary as a function of mass, CG, inertias and connection stiffness
  - Often used to determine if large flutter margins remain regardless of the range of variables
  - Results can identify flutter critical combinations & justify further investigation
  - Be cautious of number of variables; can quickly grow into large required analyses



Flutter Clearance Approach #3
By Flutter Analysis, GVT & Flight Flutter/ASE Test

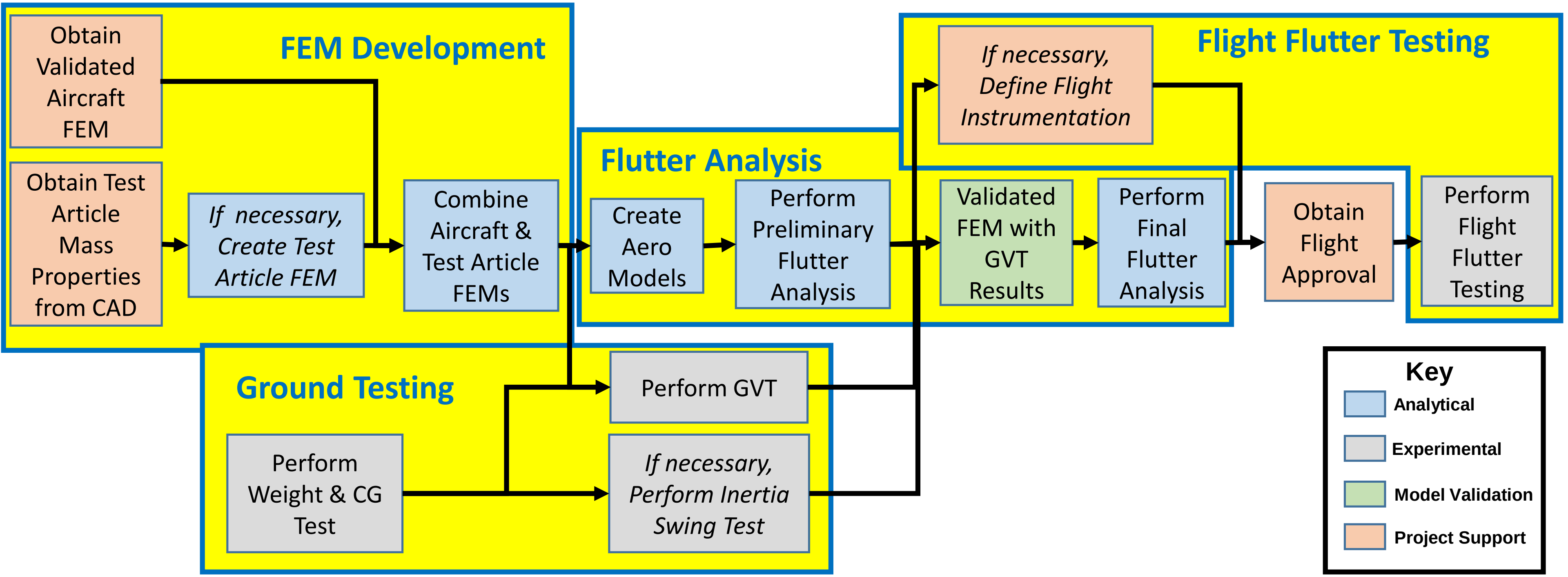
- Flutter clearance by flutter analysis, GVT, and flight flutter/ASE test
  - More standard approach used at Armstrong for all new aircraft / test article or previously certified aircraft with significant structural and/or mass modifications
  - GVT data used to validate or possibly update FEM used in flutter analyses & aid in flight flutter testing
  - Flutter analyses often conducted twice
    - Preliminary analysis using initial FEM
    - Final analysis using updated / correlated FEM from GVT results if necessary
  - Flight flutter testing provides final proof that no aeroelastic or ASE instabilities exist within planned flight envelope
  - Possible ASE instabilities are dealt with in a parallel manner by ASE analyses that may be supported by SMI ground tests before proceeding on to the flight tests



Flutter Clearance Approach #3
By Flutter Analysis, GVT & Flight Flutter/ASE Test

- Clearance by flutter analysis, GVT, and flight flutter/ASE test
  - Approach #3, most common approach used at Armstrong

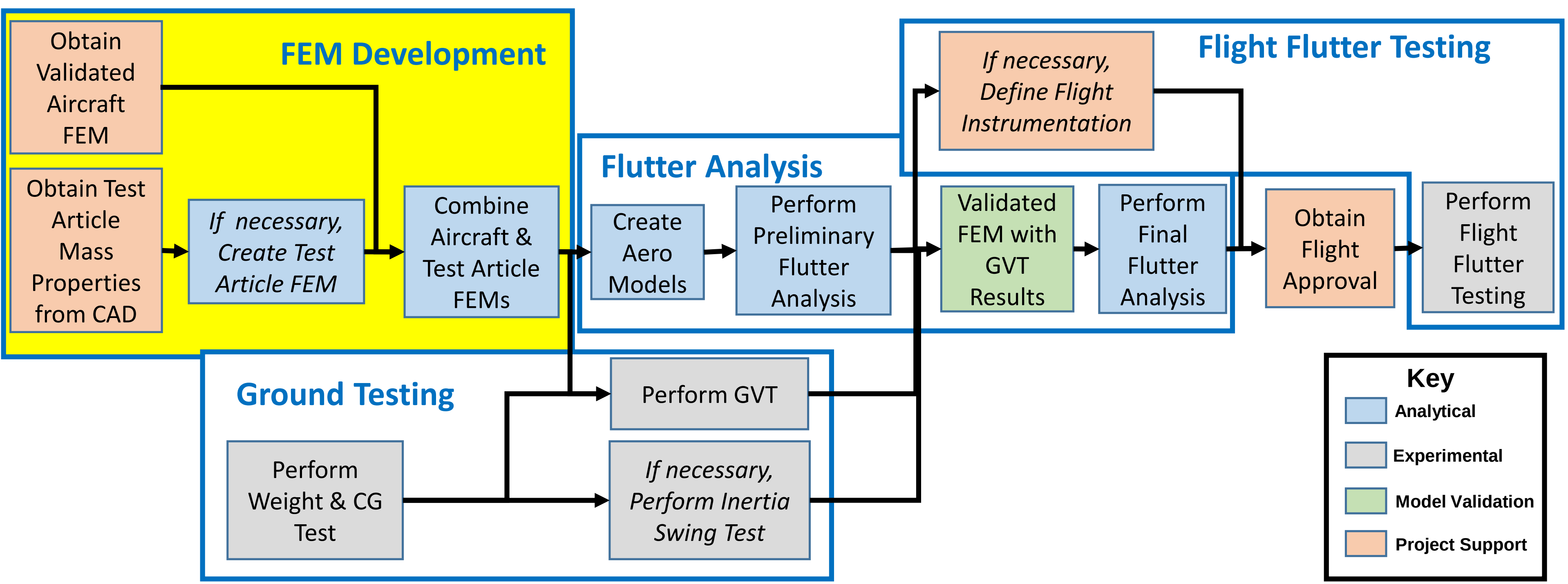
- Four major tasks to execute
  1) FEM Development
  2) Ground Testing
  3) Flutter Analyses
  4) Flight Flutter Testing



Flutter Clearance Approach #3
Task #1: FEM Development

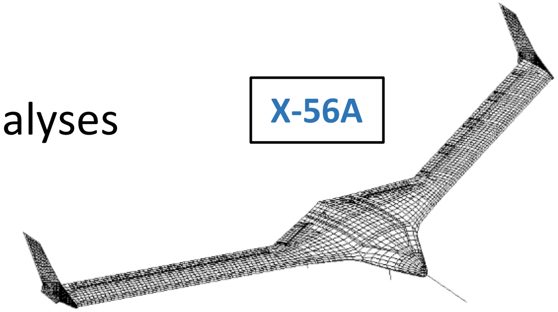
- Clearance by flutter analysis, GVT, and flight flutter/ASE test
  - Approach #3, most common approach used at Armstrong

- Four major tasks to execute
  1) **FEM Development**
  2) Ground Testing
  3) Flutter Analyses
  4) Flight Flutter Testing



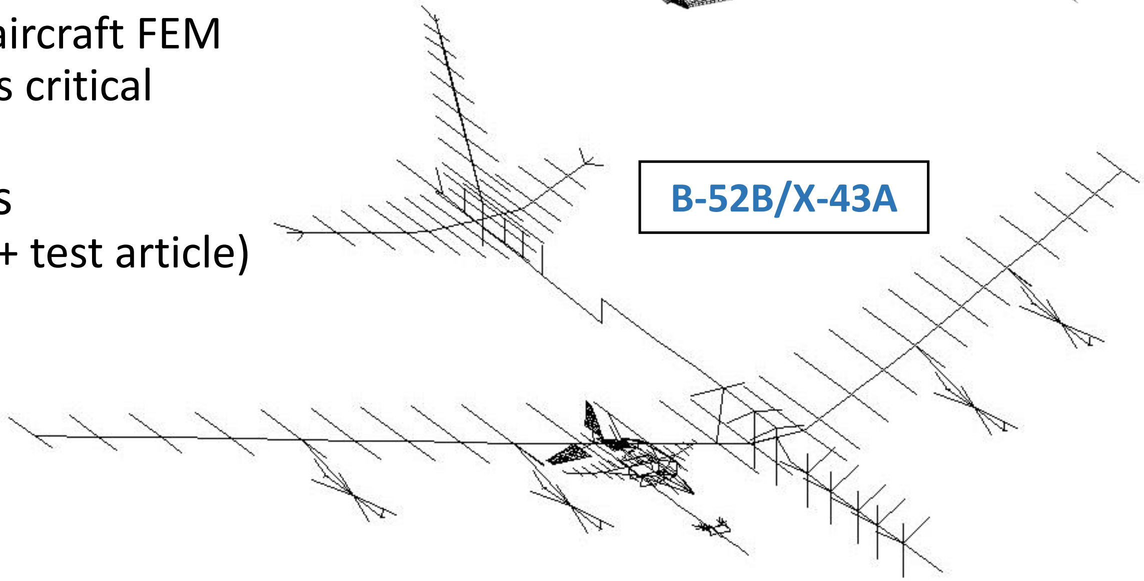
- Obtaining FEMs and/or mass properties from CAD models
  - Airframe manufacturers are reluctant to provide information
  - Divide CAD model into sub-components to assist with the creation of an equivalent beam FEM if necessary

- Creating FEMs
  - Use NASTRAN/PATRAN codes for structural modeling & analyses
  - Equivalent beam FEMs are minimal requirements



- Combining FEMs
  - Attach test article FEM to aircraft FEM
    - Connection stiffness is critical

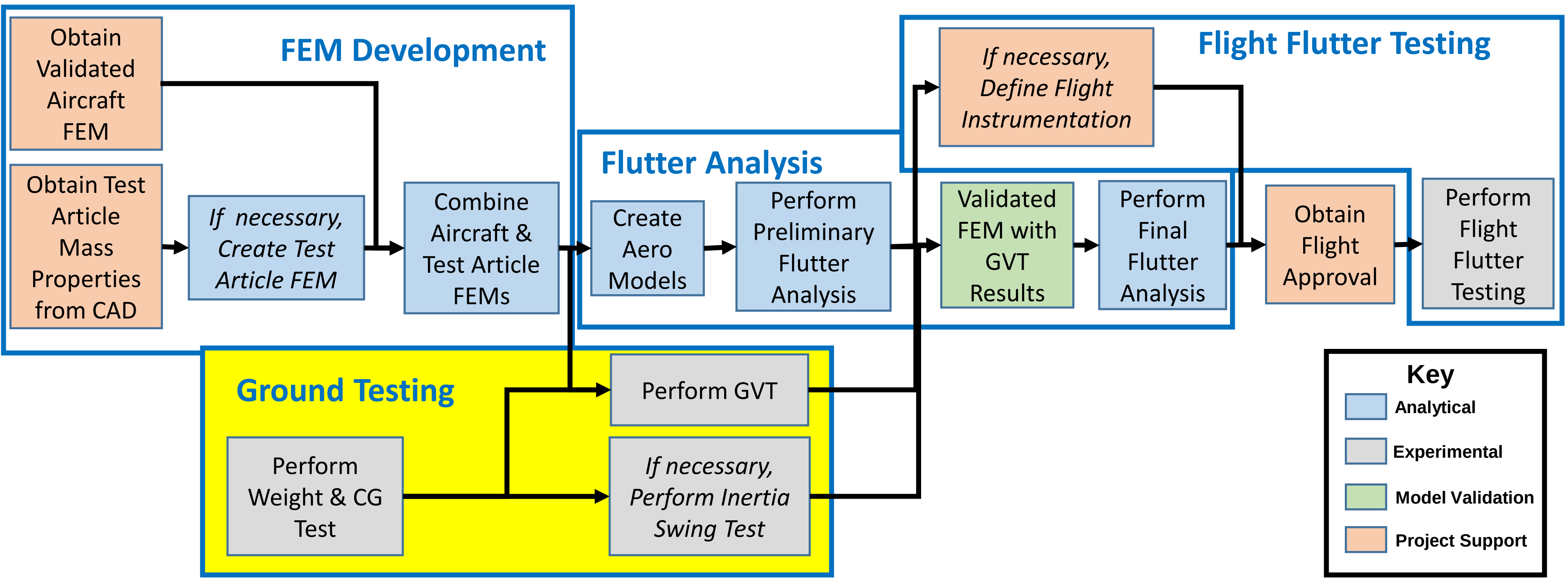
- Performing Modal Analysis
  - Obtain combined (aircraft + test article) FEM modal characteristics



Flutter Clearance Approach #3
Task #2: Ground Testing

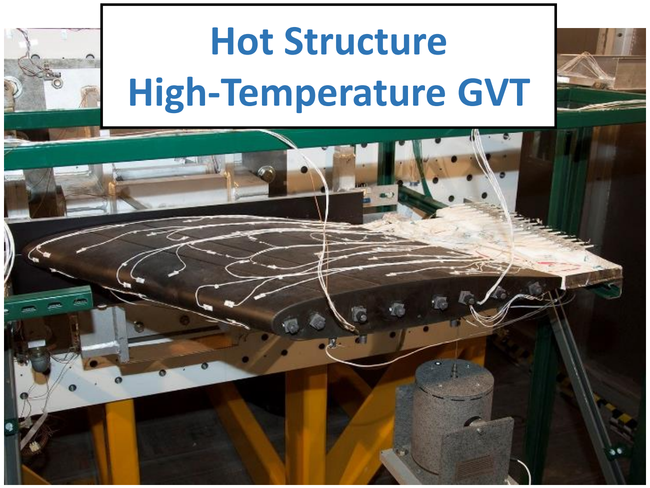
- Clearance by flutter analysis, GVT, and flight flutter/ASE test
  - Approach #3, most common approach used at Armstrong

- Four major tasks to execute
  1) FEM Development
  2) **Ground Testing**
  3) Flutter Analyses
  4) Flight Flutter Testing



Task #2: Ground Testing
Ground Vibration Test

- Goal: Conducted to identify the mode shapes, frequencies & damping values in order to validate & possibly update FEM



- GVT considerations
  - Test the aircraft / test article in all relevant configurations
    - Component level testing vs. full vehicle
    - Bound fuel loading
  - Soft support system (SSS) is usually required to simulate a free-free condition
    - Desire system with rigid body frequencies 2-4 times less than the lowest elastic mode frequency
    - Armstrong's SSS Capabilities
      - Overhead systems, from light to 14k lbs
      - Self-jacking system for aircraft jack locations, 60k-lbs capacity
      - Customized designs
  - Use proper modal test equipment
    - Sized excitation shaker, accelerometers, etc…
    - Number and placement of accelerometers
      - Perform pre-test sensor selection analysis

Task #2: Ground Testing
Mass Properties Testing

- Goal: Obtain weight, CG and moment of inertias (MOI) of test article to correlate FEM used for flutter clearance
- MOI test techniques
  - Bifilar Pendulum - Yaw inertia
    - Two suspension cables hold the test article
    - Suspension cables are equidistant from longitudinal CG
    - Yaw motion is given to test article
    - Oscillation period is measured along suspension length and mass
  - Simple Pendulum – Roll & Pitch inertia
    - Similar to Bifilar, oscillations about one axis are measured
    - Triangle suspension system used to prevent multi-axis coupling

CEV MOI

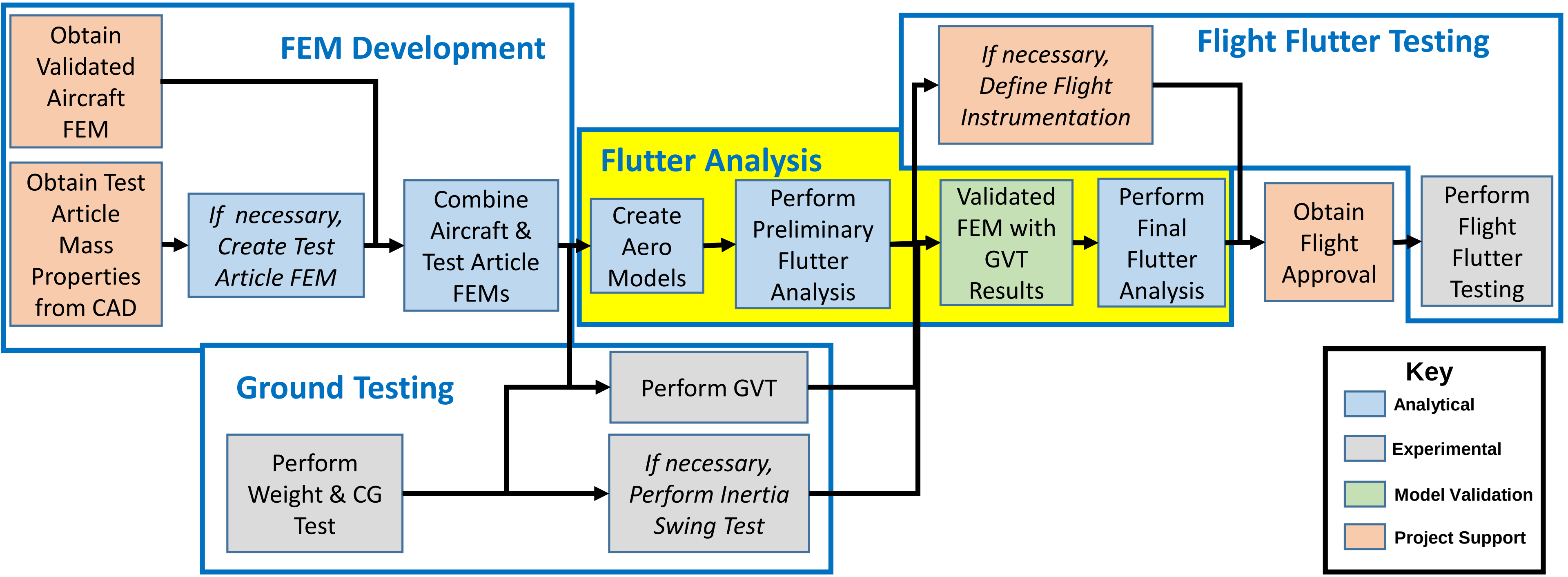
Phoenix Bifilar Pendulum

X-48B Simple Pendulum

Clearance Approach #3
Task #3: Flutter Analysis

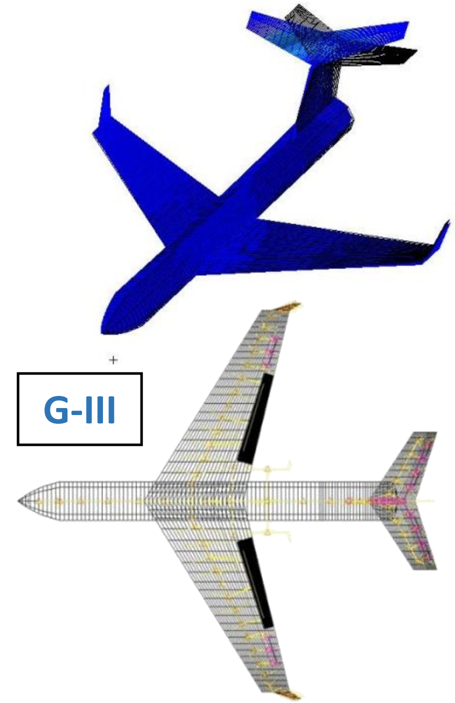
- Clearance by flutter analysis, GVT, and flight flutter/ASE test
  - Approach #3, most common approach used at Armstrong

- Four major tasks to execute
  1) FEM Development
  2) Ground Testing
  3) **Flutter Analyses**
  4) Flight Flutter Testing



Task #3: Flutter Analysis
Preliminary Flutter Analysis

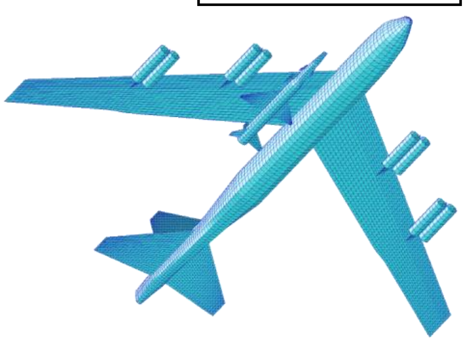
- Classical Flutter – Preliminary Analysis
  - Analysis of key flight test points for test article
    - Subsonic & Supersonic Speed Regimes: Use Frequency Domain Approaches
      - Based on ZAERO, NASTRAN, Doublet Lattice Method and/or Kernel Function Method
    - Transonic Speed Regime: Use Time Domain Approaches
      - Based on CAPTSDv (simple), CFL3D (structured), FUN3D (unstructured)
  - Create unsteady aerodynamic model for flutter analysis
    - Spline FEM mode shapes to Aero model
    - Create Aerodynamic Influence Coefficients (AICs)



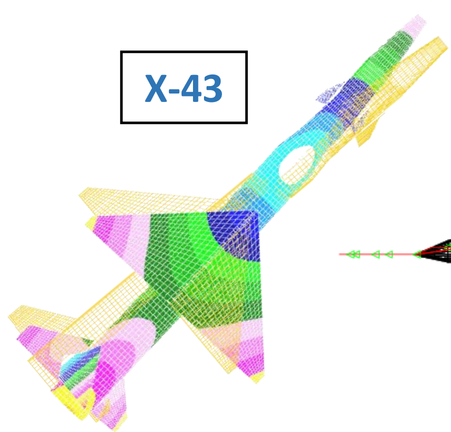
G-III

- Flutter margin required is greater than or equal to 15%

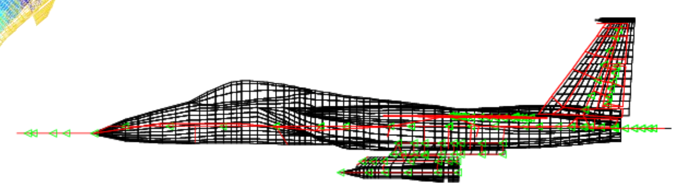
B-52B/X-43

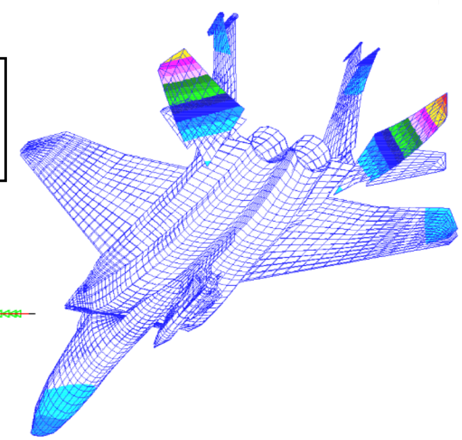


X-43



F-15 with Centerline Pylon Experiment





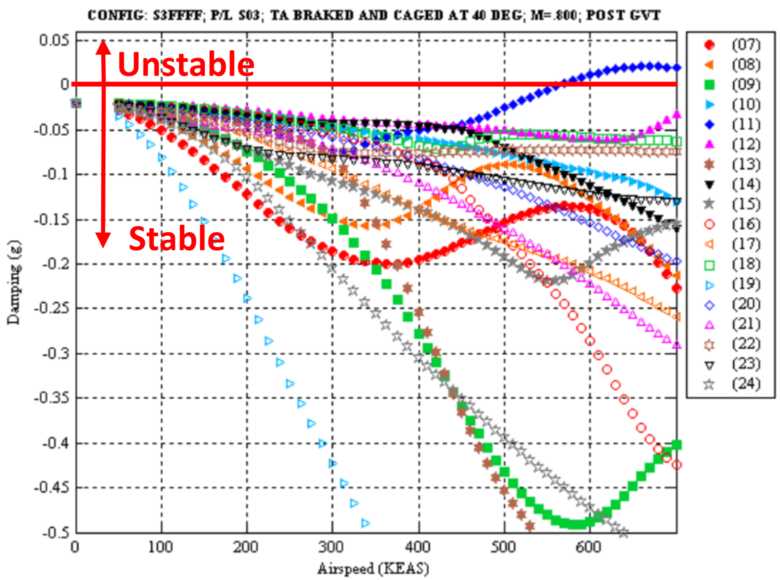
Task #3: Flutter Analysis
Validate FEM & Model Updating

- Validate FEM with GVT data by determine if FEM updating / tuning is necessary or not
  - In-house tools for FEM model updating / tuning to GVT data
    - Tuning FEM can take a long time
  - Does FEM meet the military (MIL-STD-1540C) and/or NASA (and NASA-STD-5002) standard modal requirements when compared to GVT results?
    - Modal requirements ensure FEM is a sufficiently accurate representation of test article
    - Engineering judgment on which standard is used should be made based on the test article
      - NASA Standard: NASA-STD-5002 Section 4.2.6.d
        - FEM frequencies: Error less than or equal to 5% on significant modes
        - FEM modes match: Off-diagonal terms of orthogonality matrix less than or equal to 0.1
      - Military Standard: MIL-STD-1540C Section 6.2.10
        - FEM frequencies: Error less than or equal to 3% on significant modes
        - FEM modes match: Cross-orthogonality matrix, corresponding modes are to exhibit at least 95% correlation and dissimilar modes are to be orthogonal to within 10%
- Most flight projects have demanding schedules
  - In order to accelerate the schedule after GVT & hopefully avoid a long FEM updating process, one may perform a detailed sensitivity analysis in hopes to bound the GVT results

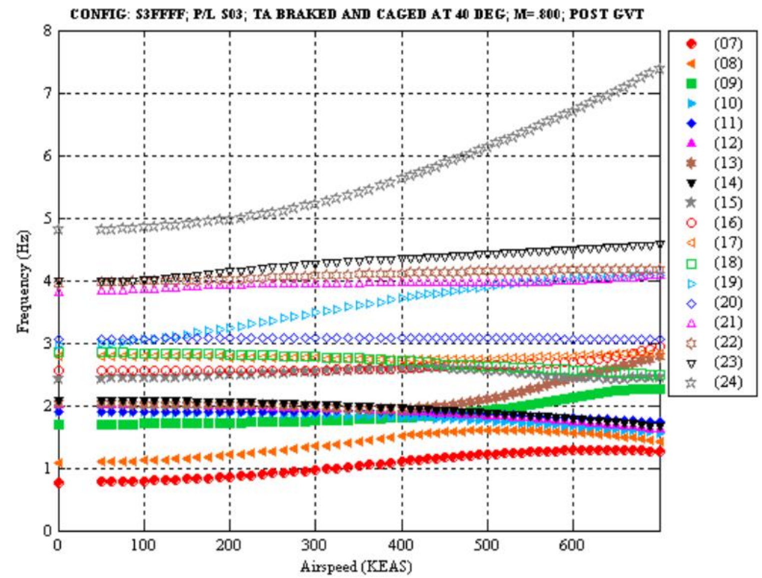
Task #3: Flutter Analysis
Final Flutter Analysis

- Final Flutter Analysis
  - Only preform if model tuning or any other FEM or aerodynamic model updates were performed
  - Redo or spot check flutter analysis at key flight test points for test article

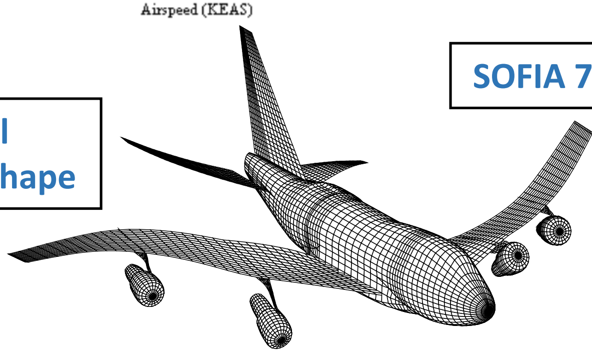
V-g, Velocity - Damping



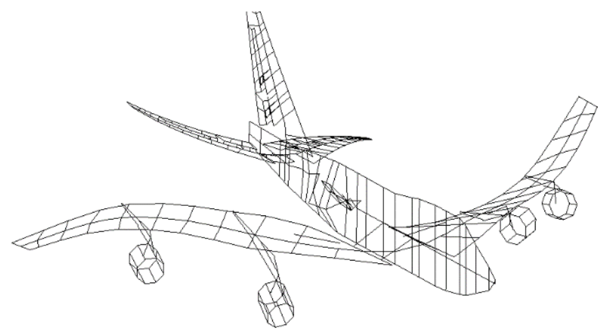
V-ω, Velocity - Frequency



Aero Model Splined Mode Shape



SOFIA 747-SP

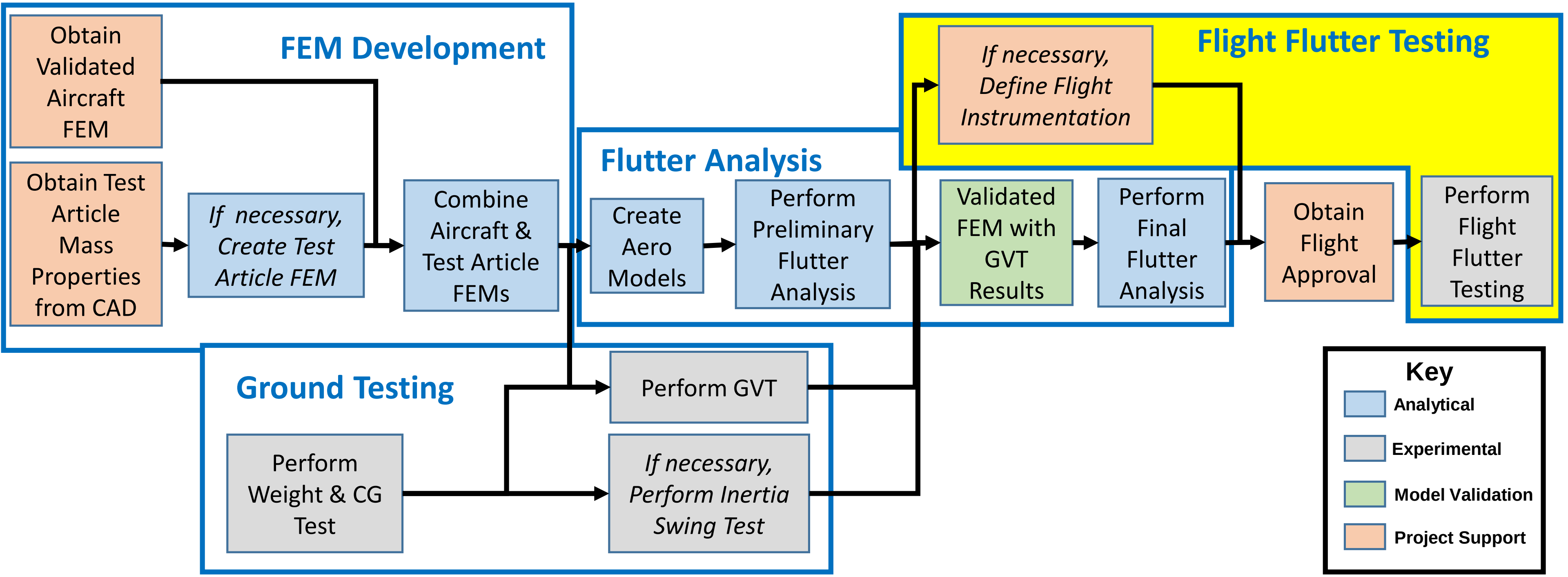


FEM Mode Shape

Clearance Approach #3
Task #4: Flight Flutter Testing

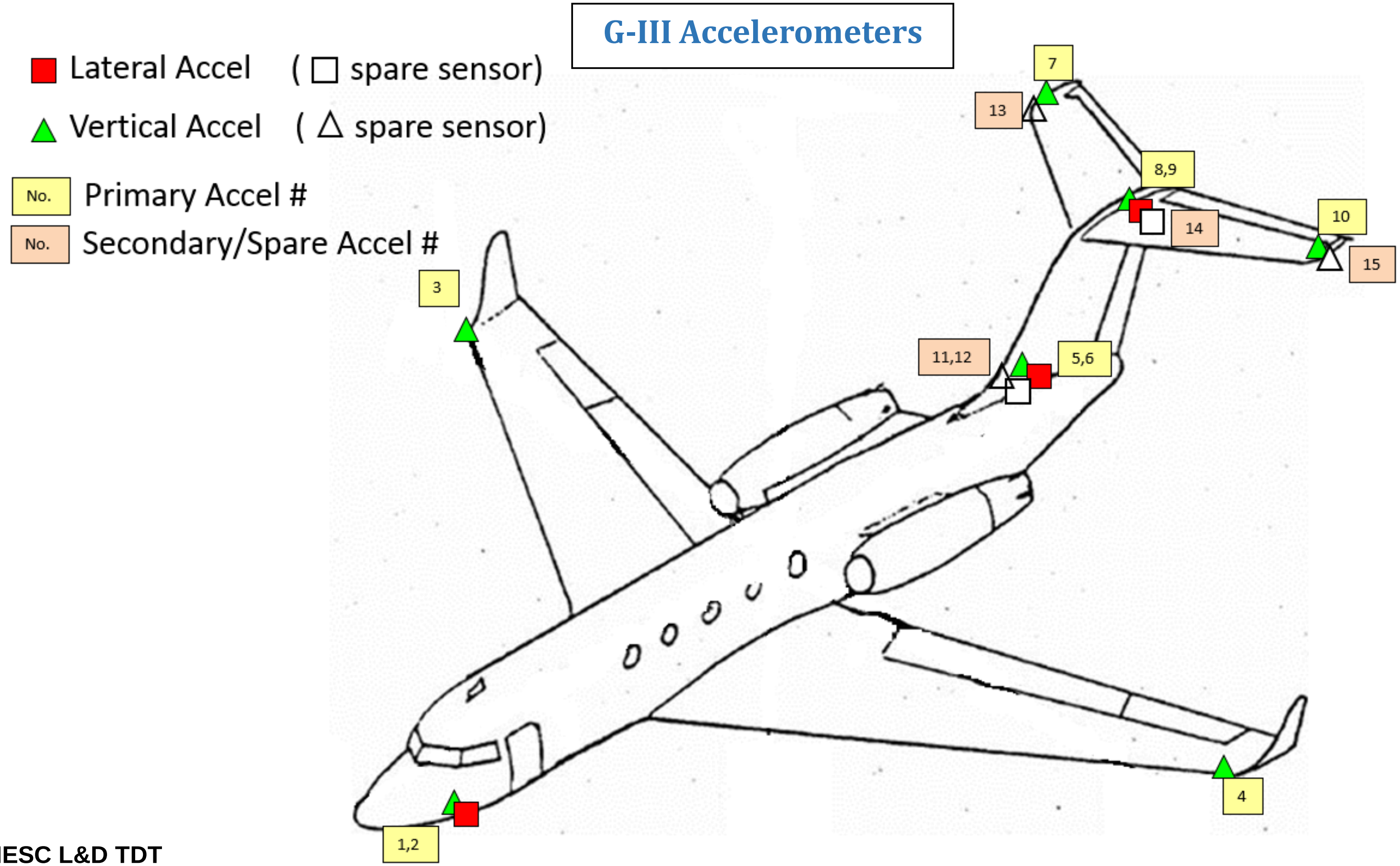
- Clearance by flutter analysis, GVT, and flight flutter/ASE test
  - Approach #3, most common approach used at Armstrong

- Four major tasks to execute
  1) FEM Development
  2) Ground Testing
  3) Flutter Analyses
  4) **Flight Flutter Testing**



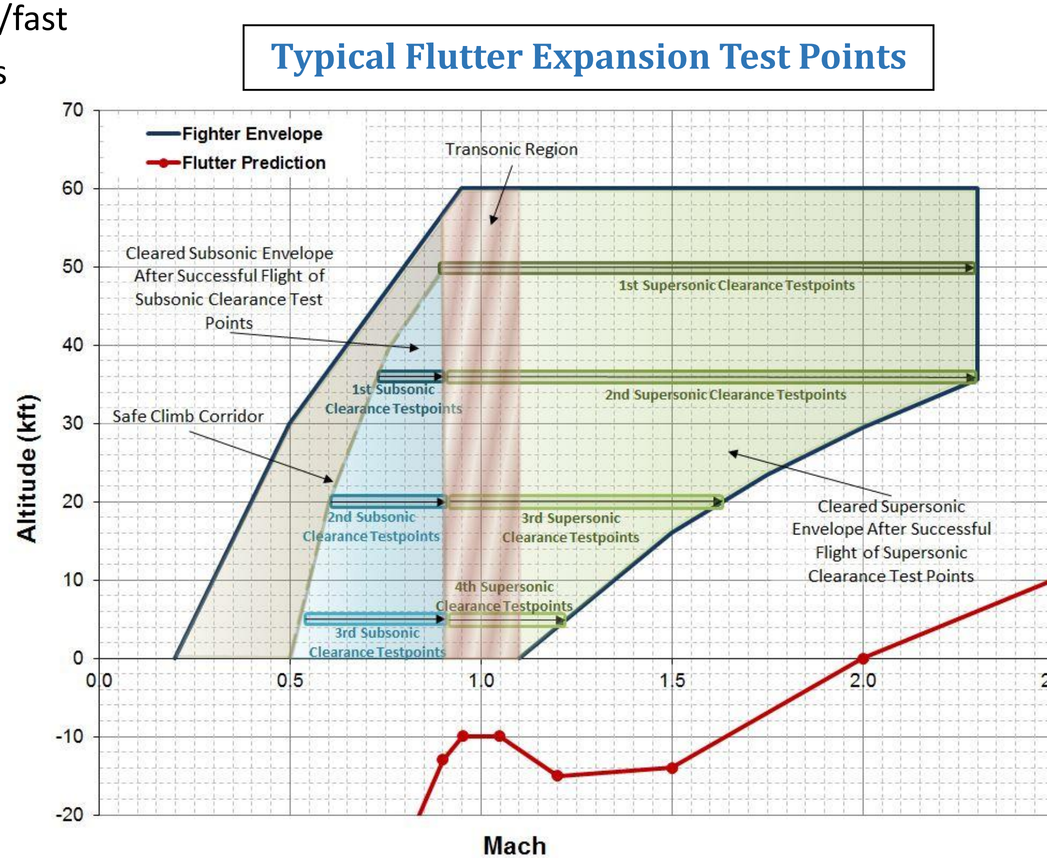
Task #4: Flight Flutter Testing
Flight Instrumentation

- Develop flight instrumentation layout
  - Flight accelerometers installed on aircraft / test article to monitor for classical flutter and provide situational awareness of any other potential instabilities
    - Locations based on predicted critical flutter mechanism



Task #4: Flight Flutter Testing
Flight Planning & Flight Testing

- Flight Planning
  - Develop flight test points using a build-up approach
    - Structural dynamics desires to strategically increased Mach number & dynamic pressure to reduce risk of encountering a potential aeroelastic instability
      - High/slow => High/fast => Low/fast
      - Usually three or more altitudes
      - Usually 0.05 Mach increments
  - Decide on maneuvers
  - Decision on means of excitation is required to excite the structural modes of interest
    - Control surface pulses
    - Turbulence
    - Flight control computers programed commands
    - On-board aero/mechanical system
- Flight Testing
  - Use build-up test point approach
  - Real-time safety monitoring & test point clearance
  - RED phone access to pilot
  - Full airworthiness demonstrated when models are correlated to flight test data

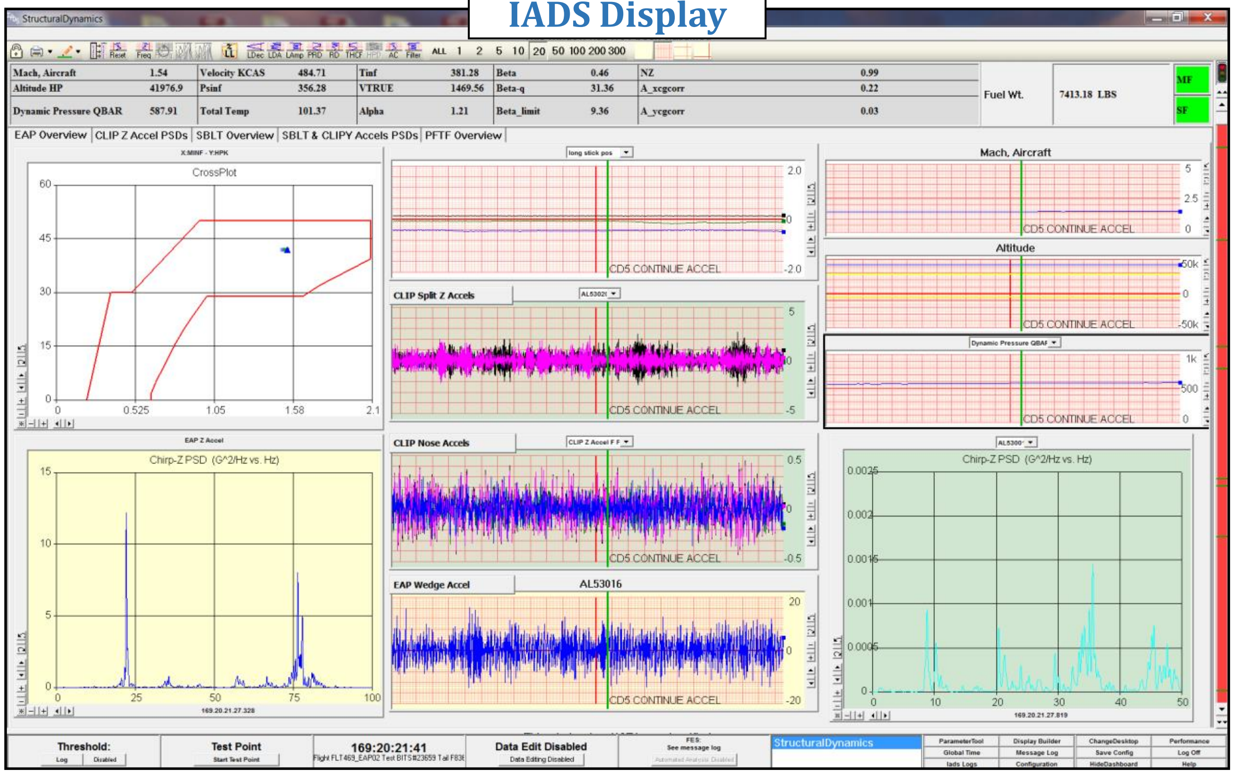


Task #4: Flight Flutter Testing Control Room Monitoring

- Develop displays for control room monitoring
  - Software: Interactive Display System (IADS)
    - Monitoring real-time time-domain (stripchart) and frequency-domain (PSD) data
    - Calculate and log frequency and damping values
    - Ability to implement external Matlab-based algorithms
    - Post-flight analysis
  - Depending on project complexity structural dynamics may have 1-4 displays to monitor

- Primary objective: Track frequency & damping versus airspeed trends to determine if there are any large and/or rapid reductions in flutter stability

IADS Display



Summary

- Airworthiness process is focused on flight safety and demonstrating aeroelastic airworthiness for the aircraft and/or flight test articles Armstrong flies
- Armstrong's system engineering process is followed to ensure all project requirements are met
- Assess the different aeroelastic instabilities which need to be investigated through the airworthiness process
- Determine what flutter clearance approach is adequate to show flutter airworthiness for the project
- Work diligently through the different tasks of the airworthiness process to maintain the project's flight schedule
  - FEM Development
  - Ground Testing
  - Flutter Analyses
  - Flight Flutter Testing

Questions

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Backup Slides

Structural Dynamics Capabilities at Armstrong

- Mission
  - Conduct aeroelastic research and demonstrate the flutter airworthiness of aircraft / flight test articles by verifying required margins for aeroelastic and aeroservoelastic instabilities

- How
  - By providing structural dynamics ground testing, analysis and flight monitoring experience and capabilities

- Capabilities
  - Ground Testing
    - Ground Vibration Test
    - Mass Property Test
    - Structural Mode Interaction Test
  - Analysis
    - Modal Analysis
    - Aeroelastic Modeling, Analyses, and Tool Development
    - Multidisciplinary Design, Analysis, and Optimization Tool Development
    - Active Flexible Motion Control and Aeroservoelastic Systems Modeling, Analyses & Tool Development
    - Unsteady CFD
  - Flight Flutter Testing
    - Flight Monitoring
    - Flight Test Planning, Data Analysis and Evaluation

Ground Testing Capabilities

- Ground Testing
  - Ground Vibration Test (GVT)
  - Mass Property Test
  - Structural Mode Interaction (SMI) Test
- Supporting Hardware
  - Test Support Stand/Fixtures
    - Swing Set, 20k-lbs capacity
    - Erector Set
    - Lifting Fixtures
    - Load Rated Floor Tracks
  - Instrumentation
    - Two GVT data acquisition systems ~340 channels each
    - Wide range of accels & force transducers
    - Wide range of load cells and position measurement sensors
    - Non-contact measurement systems
  - Excitation
    - Shakers, 7-500 lbs peak-to-peak
    - Impact hammers
  - Soft Supports
    - Overhead systems, from light to 14k lbs
    - System for aircraft jacks, 60k-lbs capacity Soft Support System (SSS)
    - Customized designs
  - Gain Control
    - Custom designs based on aircraft control laws

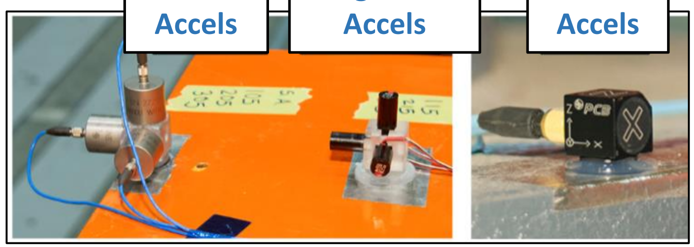
Inertia Swing Set

Erector Setup

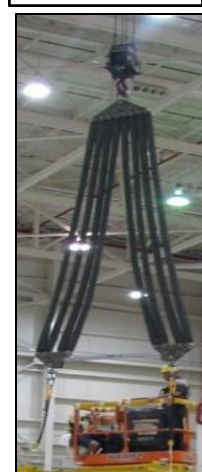
3-DOF Transducer on 100-lbs Shaker

1-DOF Force Transducer

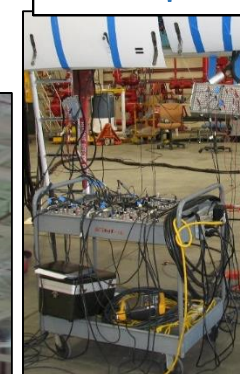
Seismic Accels | Single Axis Accels | Triaxial Accels



10k-lbs Overhead System



F-15B SMI Gain Box Setup

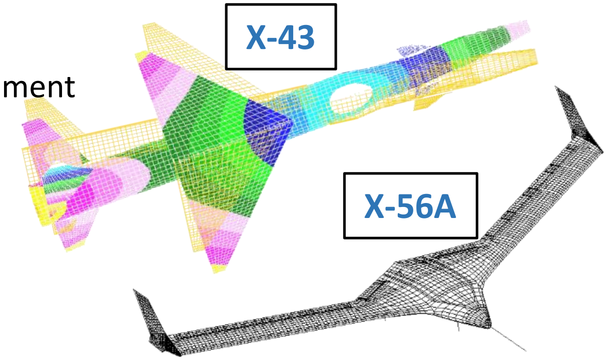


SSS

GIII on SSS

Analysis Capabilities

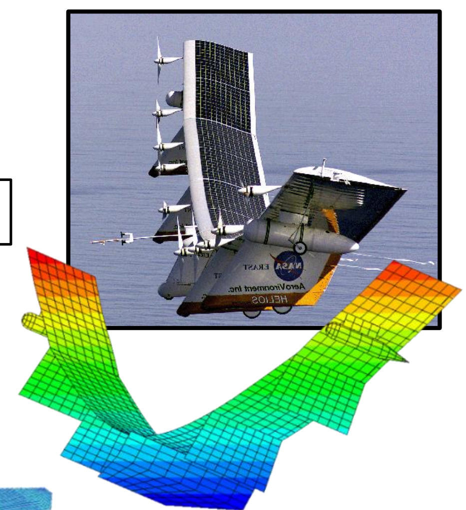
- **Modal Analysis**
  - Structural Dynamic Finite Element Modeling, Analyses & Tool Development
    - Use CAD & NASTRAN/PATRAN codes for Modeling & Analyses
  - Finite Element Model Tuning
- **Aeroelastic Modeling, Analyses, and Tool Development**
  - Flutter & Divergence Analyses
    - Subsonic & Supersonic Speed Regimes: Use Frequency Domain Approaches
    - Transonic Speed Regime: Use Time Domain Approaches
  - Unsteady Aerodynamic Model Tuning
- **Multidisciplinary Design, Analysis, and Optimization (MDAO) Tool Development**
- **Active Flexible Motion Control & Aeroservoelastic Systems Modeling, Analyses & Tool Development**
  - Aeroservoelastic (ASE) Analysis
    - Develop in-house ASE analysis tools (subsonic & supersonic)
    - Use CFD code CFL3D for transonic speed regime
  - Gust/Maneuver Load Alleviation, Flutter & Vibration Suppression, and Trim Shape Control
  - Actuator Model Tuning using SMI data
  - Aeroservoelastic Stability Analyses



X-43

X-56A

Ikhana



HELIOS

F-15B

Flight Flutter Testing Capabilities

- Flight Flutter Planning
  - Develop flight instrumentation layout, test points and maneuvers using a build-up approach
  - Develop displays for safely monitoring and clearing test points
- Flight Monitoring & Data Analysis
  - RED phone access to pilot
  - Symvionics Interactive Display System (IADS)
    - Monitoring real-time time-domain (stripchart) and frequency-domain (PSD) data
    - Calculate and log frequency and damping values
    - Ability to implement external Matlab-based algorithms
    - Post-flight analysis

Armstrong's Control Room

IADS Display