X-56 Flight Test and Lessons Learned

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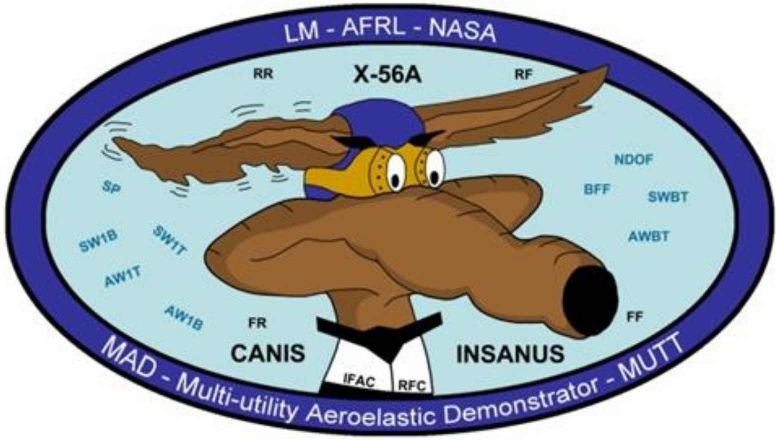
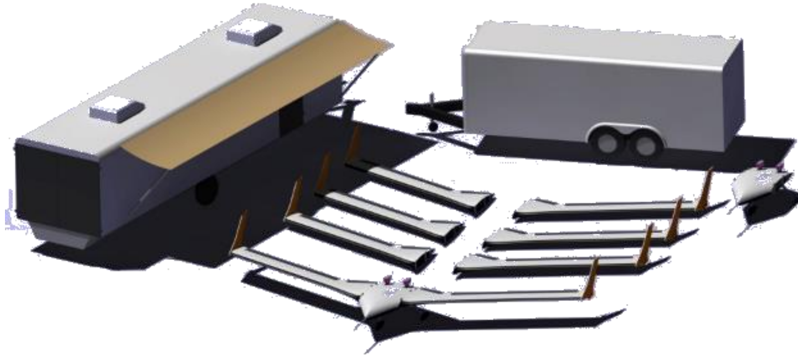
Overview

- X-56 Program Background
- Description of the aircraft
- Overview of the flight test campaign
  - The good, the bad, the ugly
- Lessons learned

X-56 Program Background

- The X-56A was developed by the Air Force Research Lab (AFRL) to explore actively controlling flutter.
  - X-56A
    - Lockheed Martin Skunkworks designed and built two centerbodies, four sets of wings, and the ground control station.
    - Became a partnership between AFRL, Lockheed Martin (LM), and NASA to conduct research into lightweight flexible wings and novel control methodologies.
    - Vehicle #1 operated by LM, Vehicle #2 operated by NASA.
  - X-56B
    - After conclusion of X-56A program, Northrop Grumman built a set of wings to interface to the same centerbody.





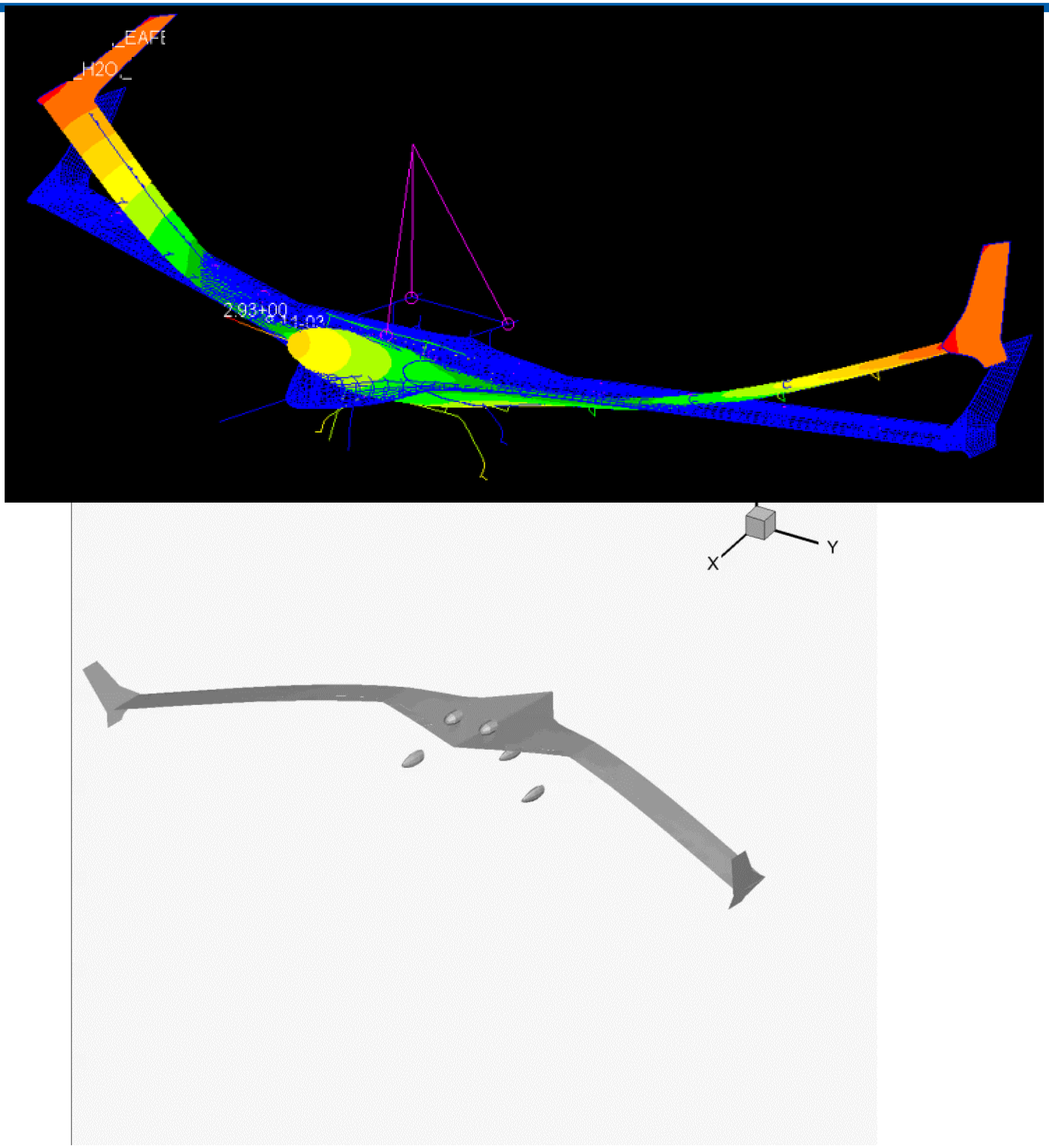
Research Objectives – Enabling Lightweight Flexibility

- Proposed future aircraft with novel configurations have more complicated aero-structural-propulsive-control interactions
  - Higher aspect ratios, hybrid wing bodies, supersonic transports with high fineness ratios all exhibit more coupling than traditional tube and wing designs
  - Increased aerodynamic efficiencies or a quieter sonic boom come at the cost of structural weight.
    - Flying wings/BWB's exhibit coupling between wing bending and rigid body dynamics (Body Freedom Flutter)
    - High fineness ratio fuselages for quiet supersonic transports start to exhibit rocket like coupling between structural modes and control, especially true when rigid body unstable

Aeroelastic Instability

- Flutter is a dynamic instability caused by the interactions of the aerodynamic, inertial, and elastic forces, and actuator dynamics.

- The specific flutter mechanism investigated by X-56 involves coupling between rigid body flight dynamics and a structural mode.
    - Short period pitch dynamics coupling with the first symmetric wing bending mode.

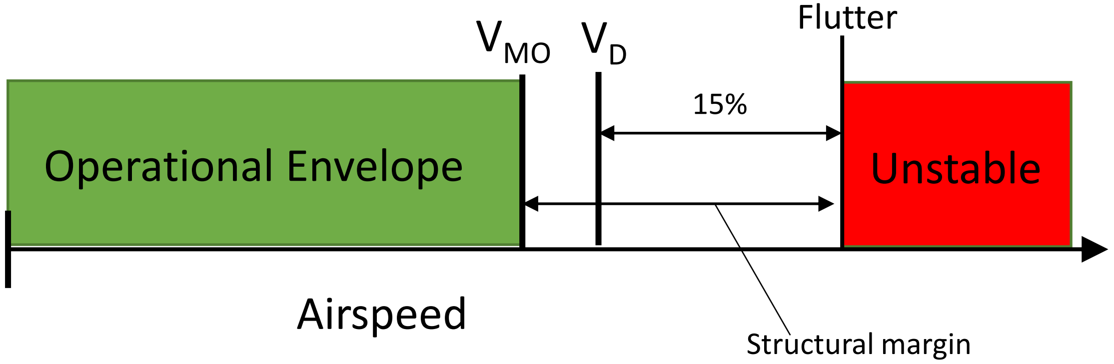


X-56 Research Objective

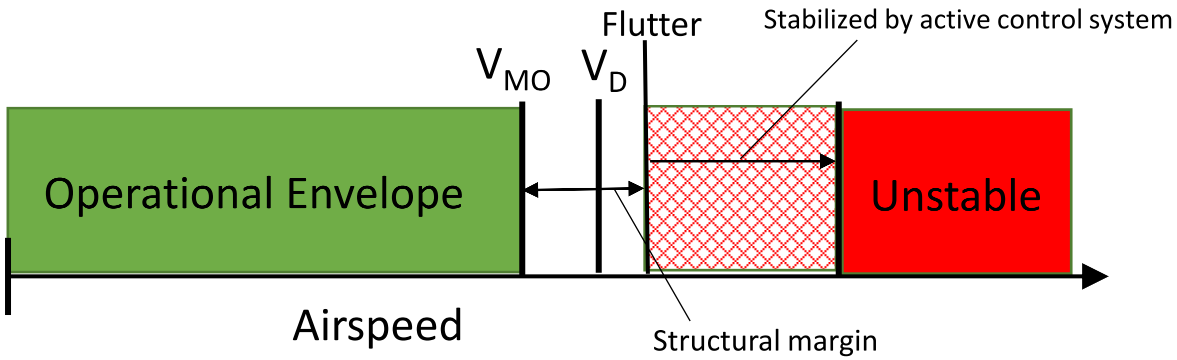
- Can the use of active feedback control stabilize flutter and provide the necessary margin and robustness?
    - What sensors and control methodologies are needed?
    - Can the aero-structural-control coupling be modeled accurately enough for control law development
        - Flutter instability prediction alone is not sufficient
        - Modeling past the instability also a significant challenge
        - Gathering data in a relevant environment is a key to advancing and validating modeling techniques
- X-56A included multiple sets of wings with the same Outer Mold Line (OML) but different structural properties.
    - Stiff wings: flutter outside the envelope, used to collect rigid body aero/control data and prove out aircraft systems
    - Flex wings: at least one flutter mode well within the achievable airspeed envelope

Flutter Margin

- Aircraft typically carry around enough structure to keep flutter 15% above the design dive speed (V_D), which has margin above the max operating speed (V_{MO})



- Instead, design the wings with less structure and let flutter occur closer to V_D and use the control system to provide the airspeed margin from instability.



- Lower structural margin = less weight = more efficient.

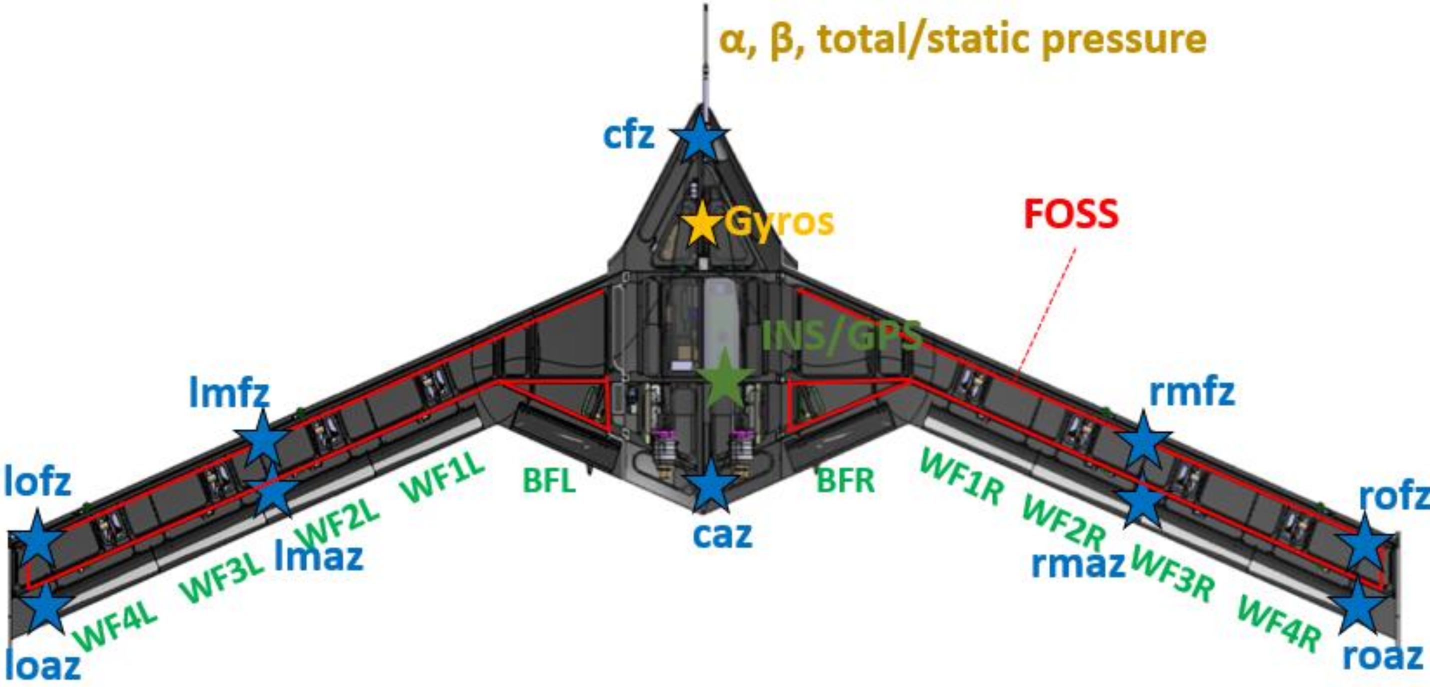
A helpful narrative …

- First airliner to utilize an all digital fly-by-wire control system was the airbus A320 with first flight Feb. 22 1987
- Boeing followed shortly with the 777 with first flight on June 12 1994
- One of the benefits of digital fly-by-wire was it enabled new aircraft to have reduced trim drag by designing for lower static stability (lower tail drag) and recovering that stability margin via the control system.
- Active structural control could follow a similar paradigm

Aircraft Description

- Vehicles:
  - 550 lbs MTOW
  - 28 ft span
  - BRS parachute
  - two P-400 JetCat engines (~90 lbf each)

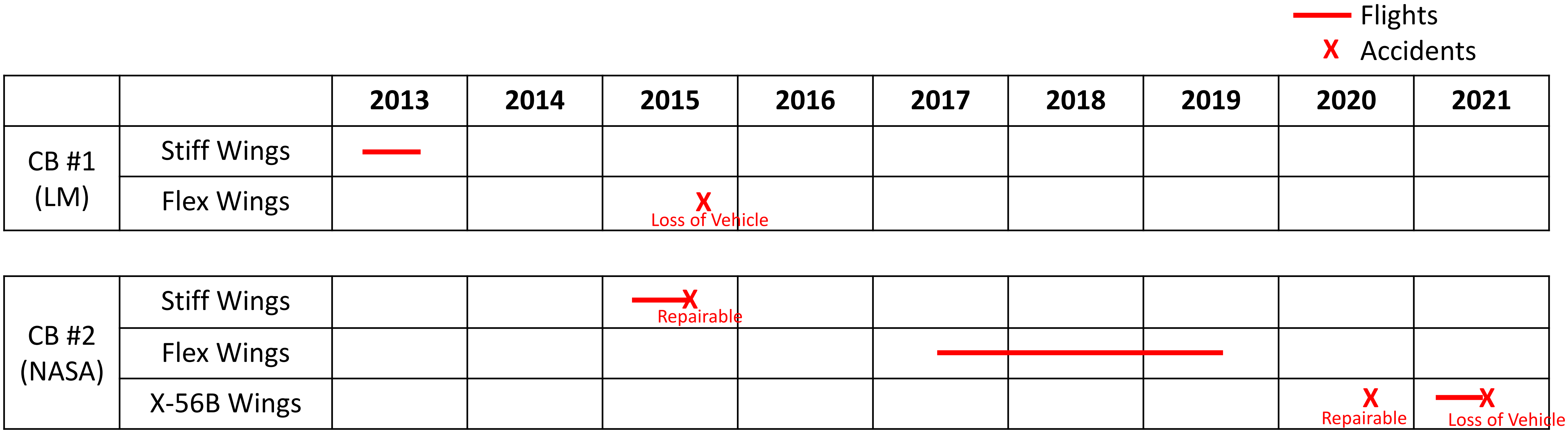
  - 10 trailing edge control surfaces
  - 3 axis high rate gyro
  - 10 z-axis accels ★
  - Fiber Optic Strain Sensing (FOSS, on 1 set of flex wings)



“Everyone has a plan until they get punched in the mouth.” Mike Tyson

X-56 Flight Test Brief Overview

- Flight test program included a total of 54 flights across the two vehicles and various wing configurations

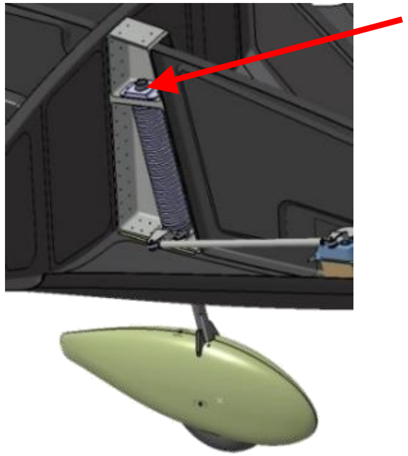


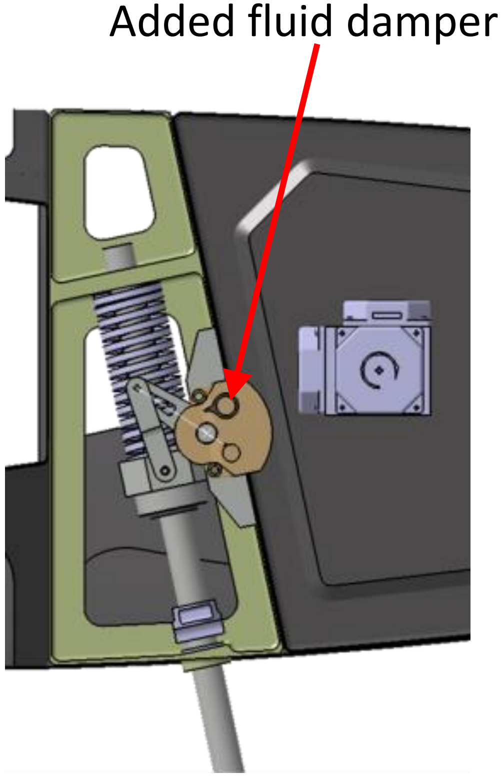
— Flights
X Accidents

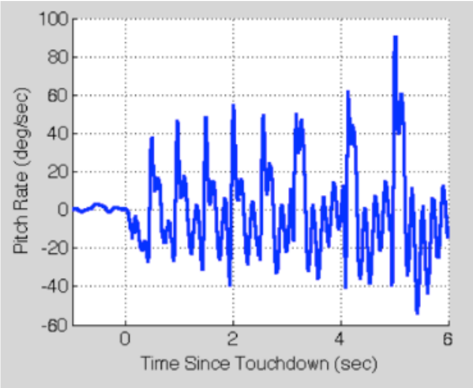
		2013	2014	2015	2016	2017	2018	2019	2020	2021
CB #1 (LM)	Stiff Wings	—								
	Flex Wings			X Loss of Vehicle						
CB #2 (NASA)	Stiff Wings			—X Repairable						
	Flex Wings					—	—	—		
	X-56B Wings								X Repairable	—X Loss of Vehicle

Stiff Wing Flight Test

- Lockheed Martin flew 8 flights with the stiff wings on CB #1
  - Flight #1 – Upon landing, the vehicle experienced a sustained nose bounce oscillation, damped out as airspeed eventually bled off.
  - Subsequently added a fluid damper, resulted in a damping ratio on landing around 0.15. Nose bounced a couple times but acceptable.
- NASA flew 8 flights with the stiff wings on CB #2
  - On the landing of the 8th flight, the vehicle entered into a divergent oscillation bouncing on the ground
- Sufficient model validation data collected to move on to flex wing research

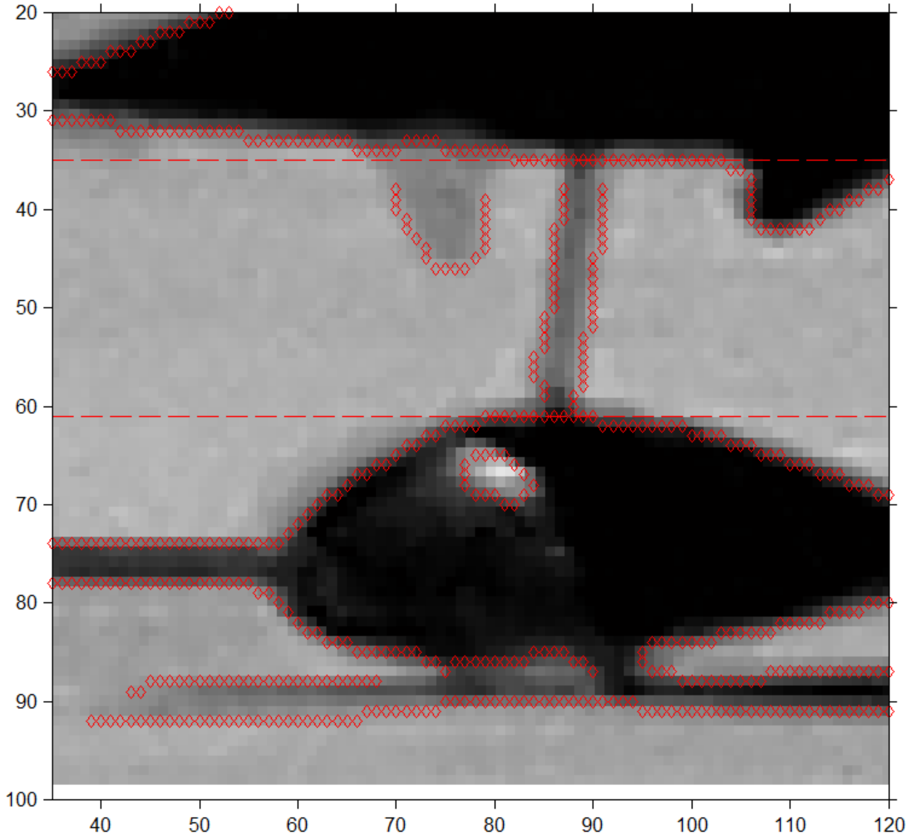






Nose Bounce Root Cause / Solution

- High resolution video of the landing showed zero nose gear compression.
- What caused the strut to bind?
  - Evaluated the nose gear strut tube on centerbody #1 (the other aircraft)
    - Nose strut was catching on the fuselage interface bushing
    - Strut tube removed and found to be permanently deformed suggesting higher loads than originally analyzed
  - Original design of the nose gear only accounted for vertical loads.
  - Including the loads/moment from the tire spinning up resulted in forces near the yield strength of the strut tube.
  - This deformation likely caused the strut to bind in the bushing
  - Takeaway: ignoring seemingly insignificant factors for something as mundane as landing gear dynamics can have significant consequences even for high risk remotely piloted flight test
- Fixes:
  - Increased thickness of the steel strut tube to account for ALL forces experienced during landing.
  - Replaced the bushing with a spherical bearing to prevent binding even in the presence of strut deformation
  - Re-balanced the spring and damping forces in the nose gear to improve overall performance

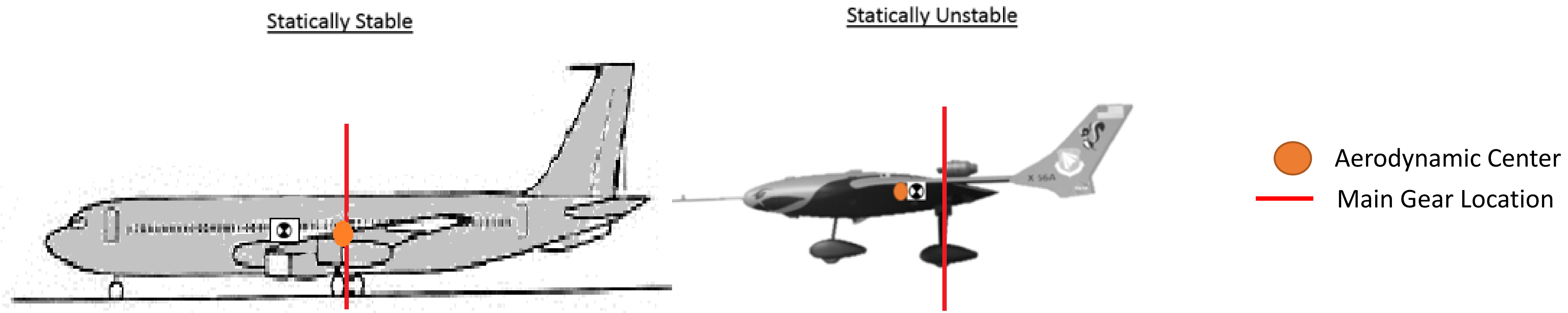


Moving on to Flex Wings

- First flight with the flex wings was attempted by Lockheed Martin with vehicle #1.
  - Immediately after rotation, the vehicle pitched up and stalled.
  - Crashed back into the ground, complete loss of vehicle.

Helpful background - Takeoff rotation

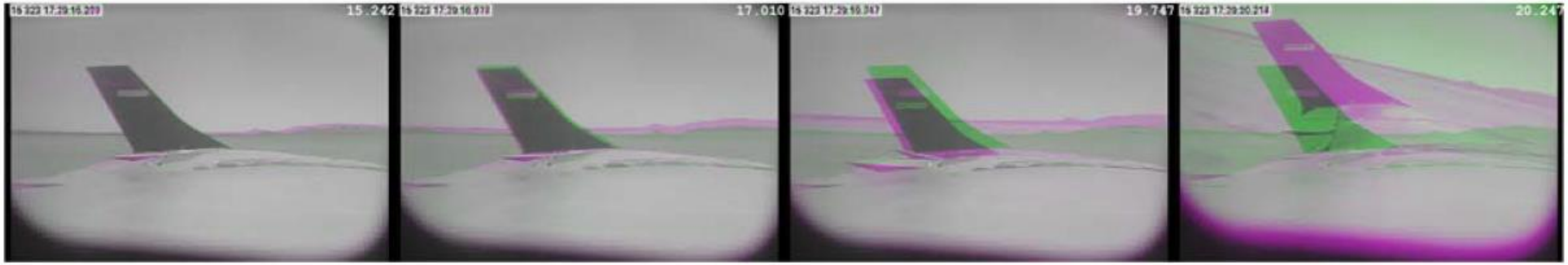
- Rotation can be thought of as building up of angle of attack and transferring the weight of the airplane from the main gear to an aerodynamic lift force on the wing.



- For statically stable aircraft (aerodynamic center aft of center of gravity), the lift force is nearly collocated with the main gear resulting in no moment change during rotation.
- For statically unstable aircraft (such as the X-56), the lift force comes in far forward of the main gear, resulting in a positive pitch acceleration during rotation.

Wing Flexibility Compounds the Issue

- Stiff wing takeoffs were bad (gear placement challenge previously discussed), but survivable.
- What changed between stiff/flex wing to make it worse?
    - During rotation, the flexible wings bend up as lift comes in. This introduces a vertical velocity at the wing tip. Vertical motion relative to the incoming airflow introduces a drop in angle of attack and thus reduction in lift.
    - For an aft swept wing, reduced lift at the wing tip results in a pitch up moment.
    - Based on calculations from wing video, it is estimated this additional pitch moment was likely enough to push the vehicle into stall.



Takeoff Rotation - Improvements

Need to reduce the pitching moment generated during rotation: reduce the force transfer and reduce the moment arm:

1. Adjusted gear geometry to sit at a higher AoA on the ground
    - Get some lift in prior to rotation. Reduces the amount of force that transfers during rotation. Essentially start bending the wings up and then rotate less to get the final lift needed for flight.
    - Essentially like a B-52, which has high wings + a bomb bay near the aerodynamic center and thus the main gear are very far aft (same problem) so it sits at a high angle of attack on the ground so it doesn’t have to rotate.
2. Moved main gear forward
    - The closer it is to the cg, the more tippy the vehicle is on the ground.
    - Went from a tip-back angle of about 18 to 10 degrees. (angle at which the airplane will flip back and sit on its tail)

Wing Flexibility also an Issue on Landing

- Prior to NASA flex wing flights, ground drop tests were conducted on the aircraft (with and without tire spin-up/down)
- Observed a significant reduction in the nose bounce damping compared to the stiff wing drop tests and centerbody only drop tests
- A significant amount of energy goes into the wings instead of the landing gear
  - Wing structure is very poorly damped compared to landing gear
  - Wing bending causes pitch coupling
  - Based on estimations, the reduction in damping from stiff to flex wings would likely result in an instability on landing
  - Landing gear design requirements for a flexible aircraft may not be the same as for a rigid aircraft

Integrated Simulation – A key development

- For both takeoff and landing, flexibility of the structure plays a significant a role in the vehicle dynamics
- State of the art in modeling:
  - Real-time piloted simulators don’t typically include structural dynamics, and if they do, they aren’t coupled back into the aerodynamics and vehicle dynamics.
  - Fully coupled structural-aero-control linear models used for design only generated up and away
    - Those models are not useful for the vehicle transitioning to/from the ground and do not include landing gear dynamics.
  - At the time of the mishaps, a piloted simulation with fully coupled structural dynamics was an active area of research for the team but not a requirement for airworthiness.
- Team pursued advanced modeling research while simultaneously working on design improvements to the landing gear based on engineering judgment and simple ground tests
  - New simulation had very little verification data but showed that landings were marginal at best
  - A controller was designed to actively damp the structural dynamics on landing to provide additional damping

Flex Wing Flight Test

- First successful flex wing flight on 8/31/2017
- Actual takeoff and landing dynamics matched the fully coupled nonlinear simulation very well.
- Flew a total of 31 flights with the flex wings thru 2017-2019.

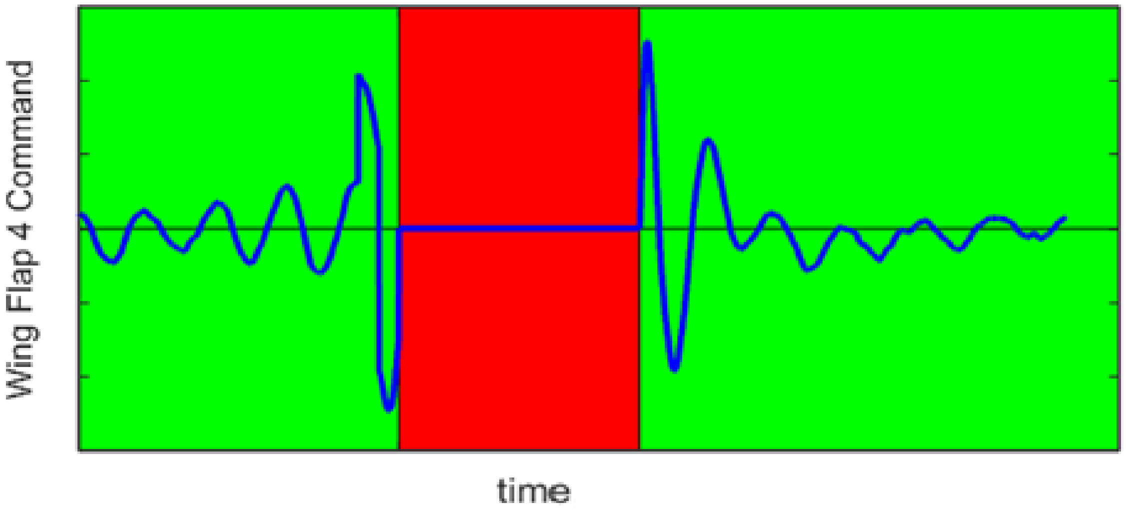
Flex Wing Flight Test

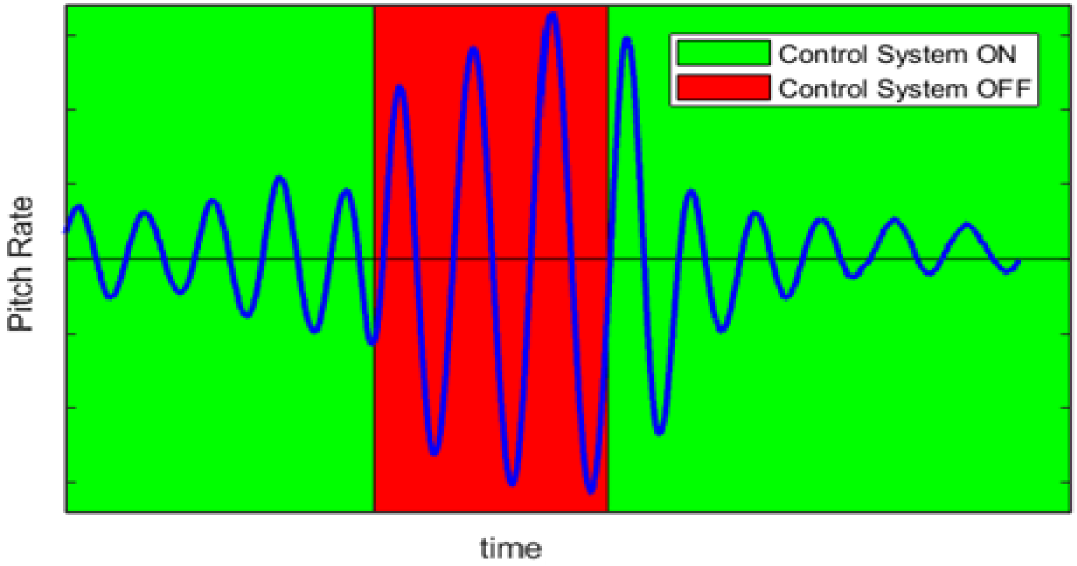
- Conducted an extensive envelope expansion flight test program.
  - Collected a significant amount of model identification data.
- Found many areas where the high fidelity up and away linear models were not matching flight data.
  - Had to retune the control laws several times, omitting entire control surfaces due to the poor matching between flight data and the models.
  - A lot of improvements were made to the models based on the flight data, however **we still don’t fully understand some of the differences**
    - But we have the data…
    - NASA-AFRL-Academia are currently working to use the data as part of a modeling workshop.
    - Hopefully this will improve the state of the art in modeling of highly coupled flexible vehicles.

Flex wing flight test

Flutter Suppression

- Successfully flew the airplane well into the flutter instability.
    - Up to airspeeds 10% past the open loop flutter instability.
    - Collected model id data and controller margin data deep into flutter.
- Conducted some test points with the control system turned off momentarily to demonstrate the flutter instability and suppression of it.





Lessons Learned

1. Be careful about assumptions based on experience with full scale and model scale aircraft
    - Be extra careful when making assumptions on this scale of vehicles.
    - **Often have limited resources, meaning decisions need to be made with less certain or no data.**
    - The physics behind assumptions for full scale design guidelines may not apply at small/medium scale.

2. Be intentional and aware of where risk is taken in the design phase
    - For X-56, the testbed (aircraft) wasn't built robust enough, too much risk in flying the asset, that it made it very difficult to get to the point of producing research results.
    - The design of the aircraft was focused too much on the end, flutter testing, and not enough on building a robust vehicle.
    - Takeoff and landing were more risky than flutter testing, in part because the landing gear design was constrained by the parachute landing case rather than being optimized for normal landings
    - **Want your risk in the research under test not the normal operations of the testbed.**

3. Airworthiness process tailoring
    - Get waivers for things that don't make sense for a small/medium-scale high risk vehicle
        - Class III software (for reduced testing requirements), environmental testing, reliability of components, etc.
    - But don't treat it like you are building a vehicle for a youtube video
        - Robust connectors, good models and simulations, good human factors for ground stations, reliable command and control links, high quality video and instrumentation etc.
    - Don't treat all incidents like mishaps (Mishap Exclusion Memo)
        - For high risk, small scale projects, allow for failure. Learn from it, fix it, then fly again (all overseen by the normal airworthiness process).
        - Formal mishap investigation process is too much bureaucracy, and it can nearly kill projects of this scale.

Lessons learned

4. Risk acceptance:
   - If you take too much risk, you will end up not achieving your end result. But if you take too little risk, you will exhaust your budget before ever producing results.
   - X-56 design phase through the loss of the first vehicle was likely on the too much risk side. But then with only one vehicle left we swayed to the other side and became too risk adverse.
     - Accomplished our research but by then we had little programmatic support, AFRL kept us going just enough to get past flutter.
     - Vehicle was capable of likely flying deeper into flutter and possibly getting close to the second flutter mode.
     - **<u>Need to thread the needle between too much or too little risk acceptance</u>** and constantly be adapting.
   - Learning from actual flight experience an be a powerful way to accelerate research if you can get the risk posture just right
5. Build multiple vehicles at the beginning and plan to lose and airframe or two for this scale of testing
   - For this scale, the cost of the vehicles ends up being small compared to engineering labor over the life of the program.
   - Along same lines as #4, early in the program, assess the risk level. One vehicle is likely going to make you too risk adverse and drive the program to cost too much in engineering.
   - Having multiple vehicles ready to go allows a “failure is an option” mindset, once loss of vehicle equates to loss of research you can no longer accept as much risk.
   - For X-56, if we could do it over, **<u>3 vehicles likely would have been the sweet spot</u>**
     - Could have taken more risk with second vehicle and likely made it to flutter far quicker.
6. Perseverance
   - Going through multiple mishap investigations and facing challenging decisions with no data, there many days the team felt like it was an impossible problem.
   - However, with a tenacious and creative team, and the right support across the organizational leadership (AFRL and NASA) the team always seemed to find the missing piece and the courage to see if it actually worked in flight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Questions?