Contributions to Airplane Design & MDO Integrated Education & Research

Eli Livne
William E. Boeing Department of Aeronautics & Astronautics
University of Washington
Seattle, WA

USAFRL / AFOSR
July 14, 2016

Background – Observations

(reflecting broad-brush personal views)

- The growing power and user-friendliness of computer codes adds strength to undergraduate and even graduate aircraft paper design studies.
- The learning curves are often steep and resulting designs by students may lack realism or are poor. Multidisciplinary integration is also weak.
- Focusing on computer simulation studies in design without substantial hands-on experience often leads to flawed results.
- Computer simulation design experience is incomplete without hands-on experience and the knowledge, based on experience, of how and when different analysis / computer models may be useful as well as the limitations of various computer models.
- Very rarely is MDO introduced to aerospace students in the U.S., and even more rarely is it part of their flight vehicles design experience.

Observations - continued

- The current low-cost availability of off-the-shelf propulsion systems, as well as actuation, sensing, control, and other systems for small UAVs, plus the revolution in manufacturing, have made Design, Build, Fly flight vehicles design projects more wide spread. At most universities they are the capstone design projects.

- Common DBF challenges require more emphasis on avionics / controls and less on airframe design. The engineering depth and thoroughness of common DBF projects, regarding the airframes developed, are usually quite limited.

- There is very limited impact of state of the art airframe design challenges on the undergraduate curriculum, if at all.

- There is very limited experience at the undergraduate level of the full airplane design process, including analysis, design, ground tests, flight tests, team function, budget and schedule constraints.

- To offer the full airplane design experience at the undergraduate level is expensive (wind tunnel models & tests, software required, ground and flight test equipment required, etc.), but costs are coming down.

- Graduate level research in airplane design and MDO affects a very small number of students.

Key Elements of the UW Capstone Airplane Design Program

- Design challenges reflect actual flight vehicle design challenges
- Design projects, in addition to educational goals, are aimed at making contributions to flight vehicle design state of the art
- The project team design experience is realistic and reflects the inner working and challenges of a small flight vehicle design organization
- Significant hands-on experience and analysis / test correlation
- State of the art analysis, design, and testing tools
- Strong support from local industry (Boeing, AeroTec, ATS, etc.) and alumni who are now experienced engineers.

Key Elements of the UW Capstone Airplane Design Program

- 25 seniors. Organized into a small "company", with two project leaders, and discipline team leaders.
- Commercial quality wind tunnel tests at the UW's Kirsten Wind Tunnel (www.uwal.org)
- Component aerodynamic tests at the UW's 3x3 wind tunnel.
- Static structural tests and Ground Vibration Tests (GVT).
- Aeroelastic wind tunnel tests, when necessary.
- Commercial quality Finite Element (FE) structural, structural dynamic, and aeroelastic analysis – NASTRAN.
- STAR-CCM+ CFD (www.cd-adapco.com).
- Matlab & X-plane flight mechanic simulations.
- Propulsion systems experience: piston engine/propellers, electric motor/propellers, ducted-fans, electric ducted fans, small jet engines.
- Composite construction: Carbon, Glass Fiber, Kevlar.

Design Challenges Tackled Over the Years by Seniors in the University of Washington's Capstone Airplane Design Program
(working within the 20 weeks course constraints in the past)

- 2005 – A supersonic business jet configuration.

- 2006 - A 3-surface supersonic business jet configuration.
- 2007 – Conversion of the F16-XL into a low-sonic boom NASA research X airplane.

- 2008 – A Quiet transonic passenger airplane.
- 2009 – A jet powered quiet supersonic configuration.
- 2010 – A jet powered quiet supersonic configuration with improved aerodynamic characteristics relative to the 2009 design.

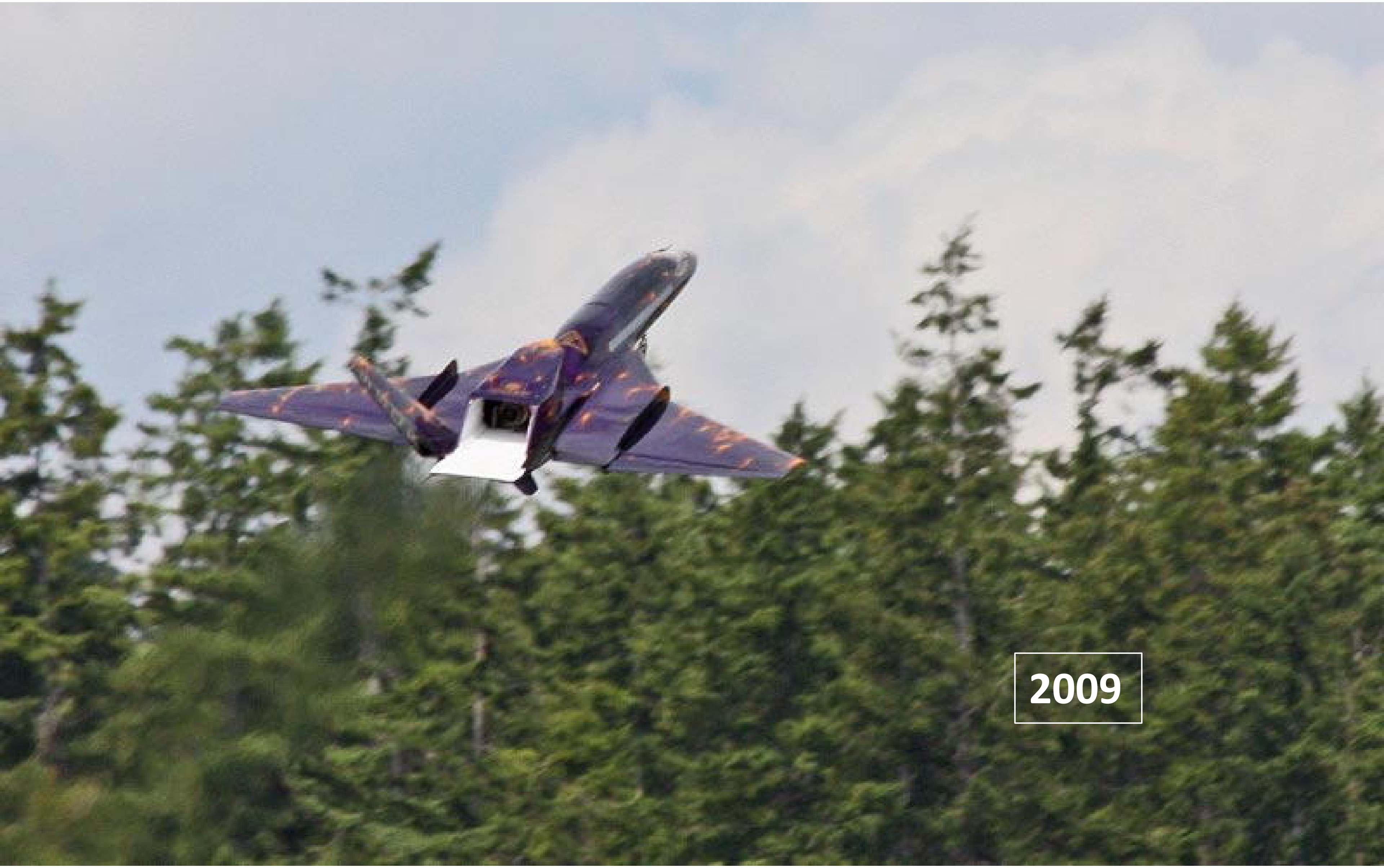
- 2011 – A strut-braced high Aspect Ratio wing passenger airplane with significant aeroelastic effects.

- 2012 – A 777-X type transonic passenger jet with very high Aspect Ratio.

- 2013 – A tailless supersonic configuration.
- 2014 – A research UAV for studying aspects of tailless supersonic configuration characteristics.

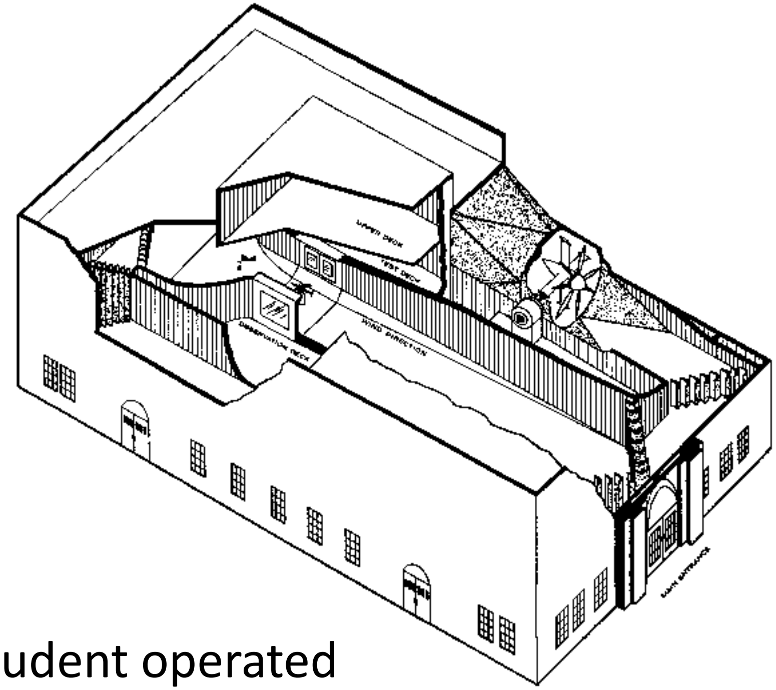
- 2015 – A research UAV for studying aspects of tailless supersonic configuration characteristics.


2011

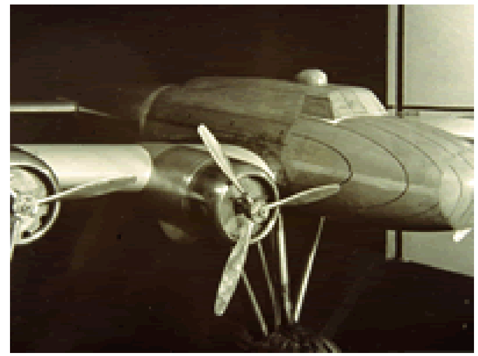

2009

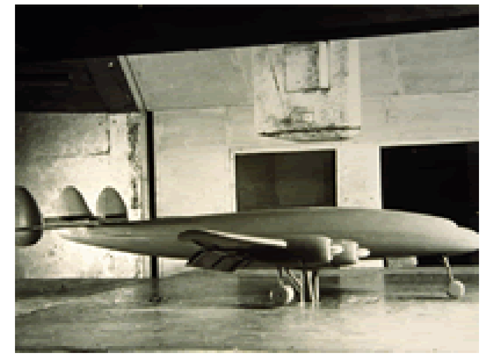

0

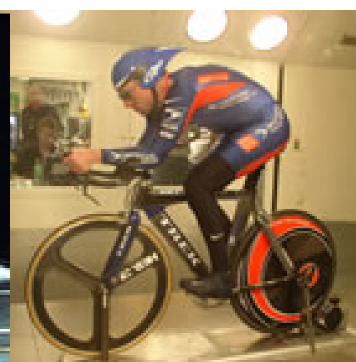
The University of Washington's 8x12ft Low-Speed Kirsten Wind Tunnel

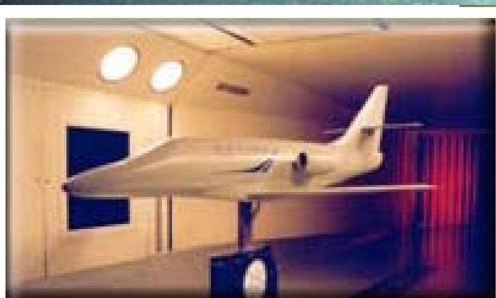


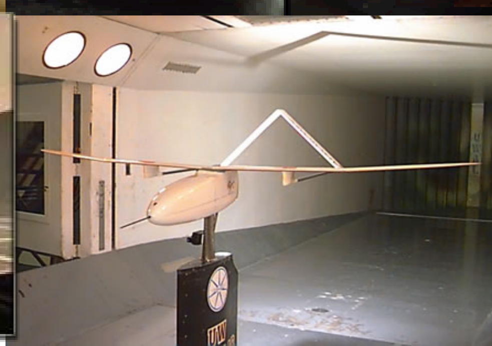
Student operated









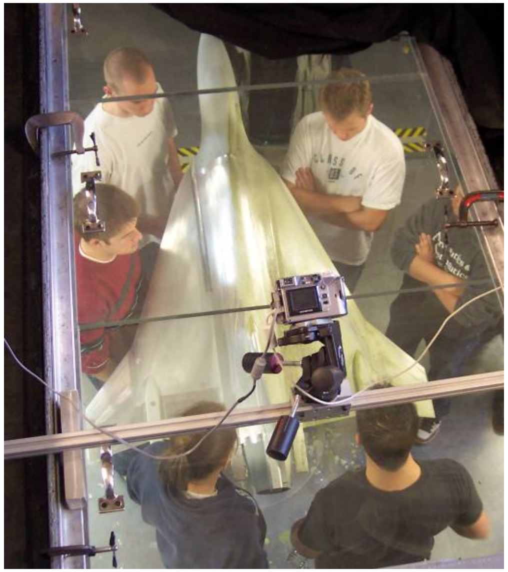


Significant Low-Speed Wind Tunnel Applied Aerodynamics Experience

Example: the 2007 F-16XL Senior Design Kirsten Wind Tunnel Test

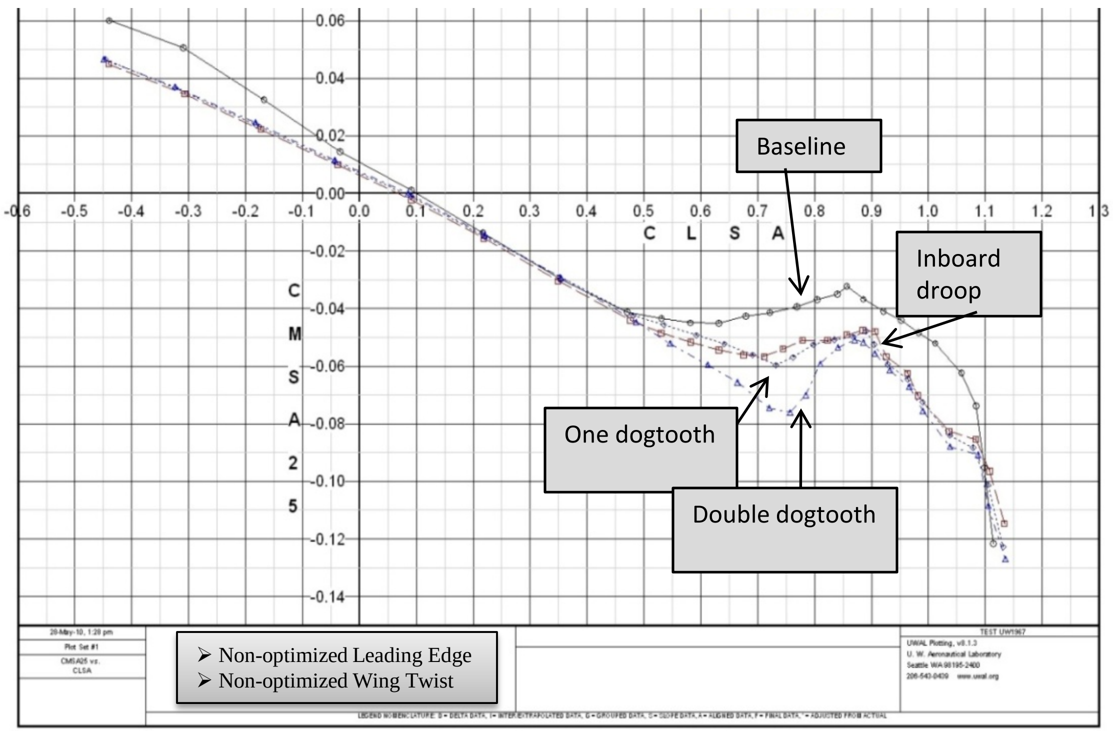
- Testing and model design/ fab funded jointly by Aeronautical Testing Service, UW Aeronautics and Astronautics department, and Boeing. (Model by ATS.)

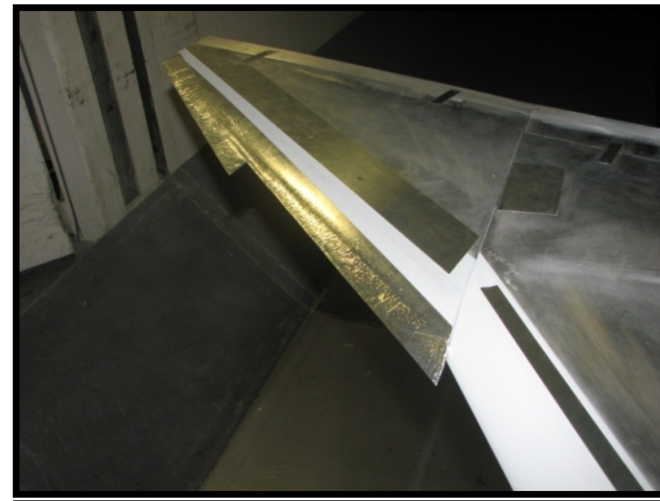
- Eleven, 10 hour shifts of testing, >300 Runs
- F-16XL Baseline configuration
- Multiple low- boom features tested;
  - Low- boom forebody “glove”
  - Reduced shock canopy shape
  - Several leading gloves
  - Wing tip span extensions
  - Control surface mods
  - Trailing edge extensions
  - Ventral fins and wing fences

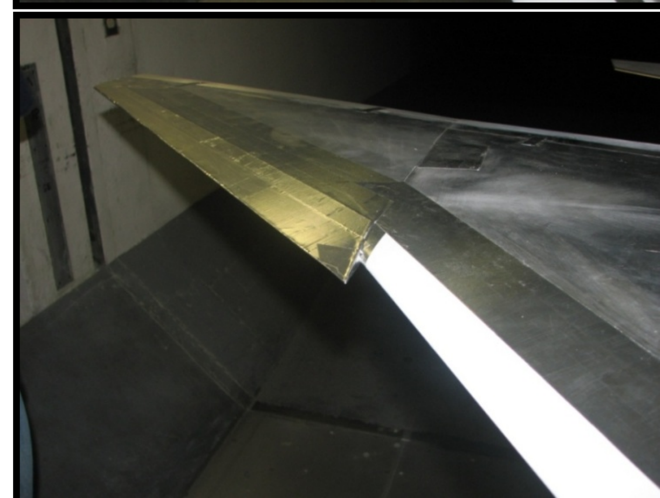


- **Tail Sizing:** Tails designed small so they could be incrementally built up to the appropriate size

2010 Pitch Stability

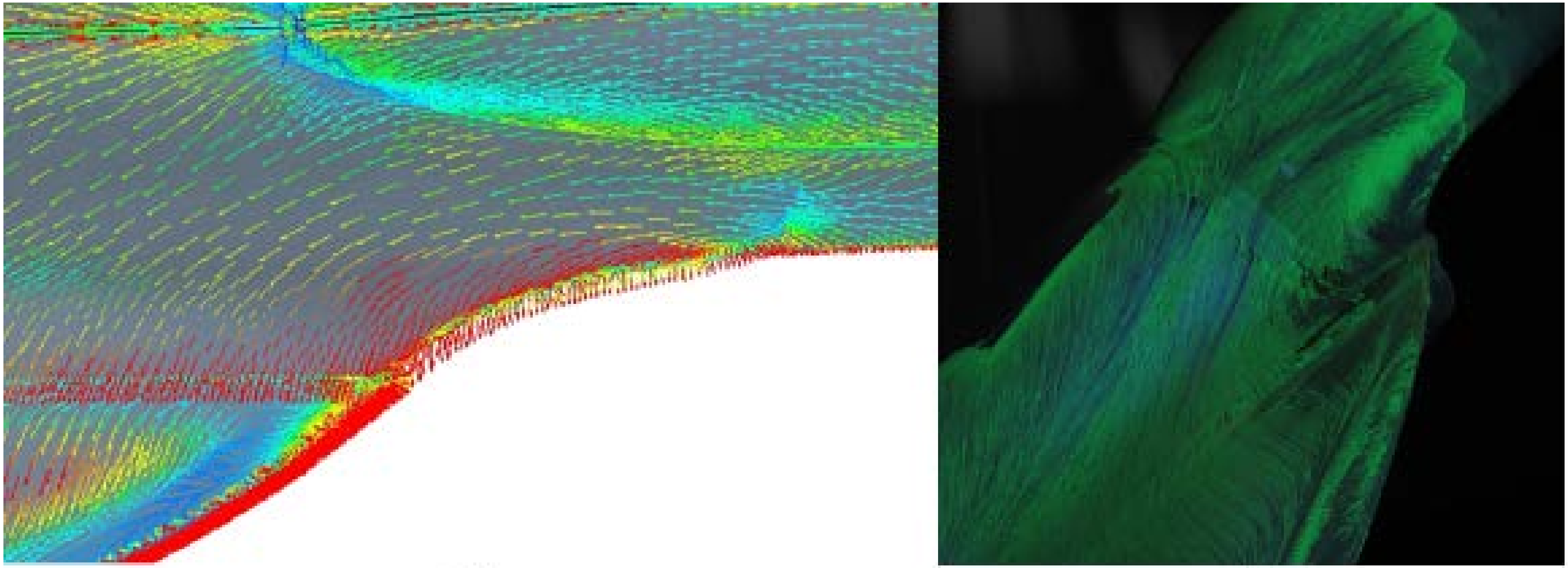






-Significant Analysis / Test Correlation Studies

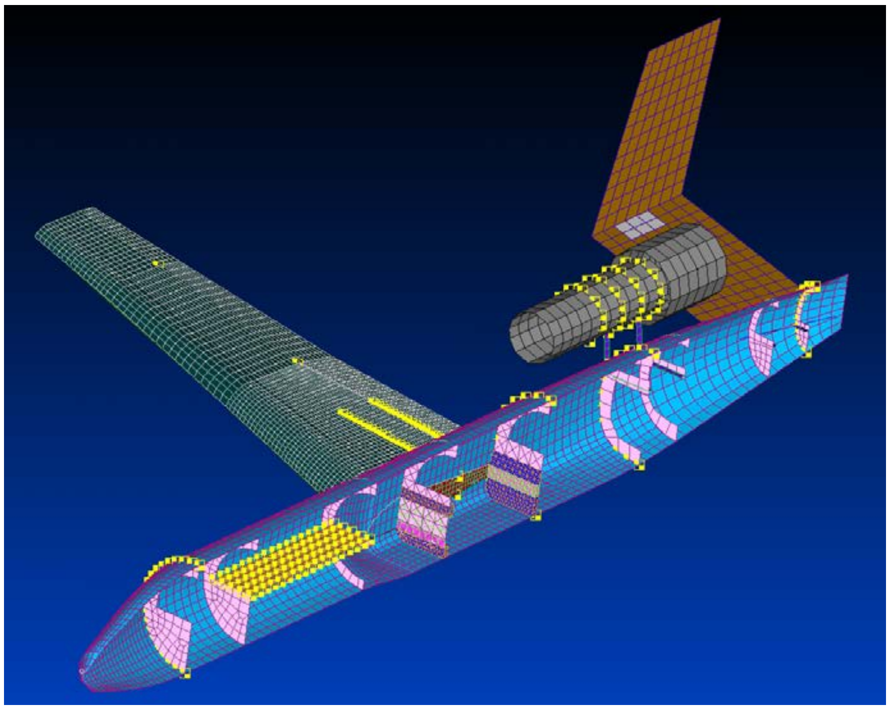
Analysis vs. Actual Physics
- Reliability and usefulness of simulation
- Good simulation practices



(a) (b)

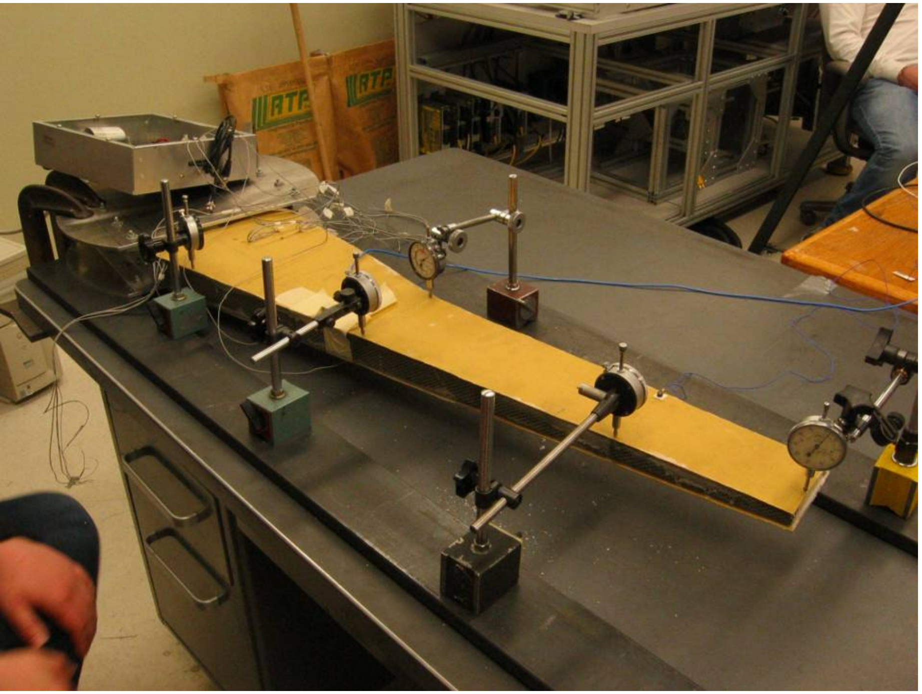
Comparison of wall shear stress in STAR-CCM+ (a) to china clay flow visualization (b) for the F-16XL at the wing leading edge at 30 degrees angle of attack.

Finite Element Structures Model Including Non-Structural Mass Distribution

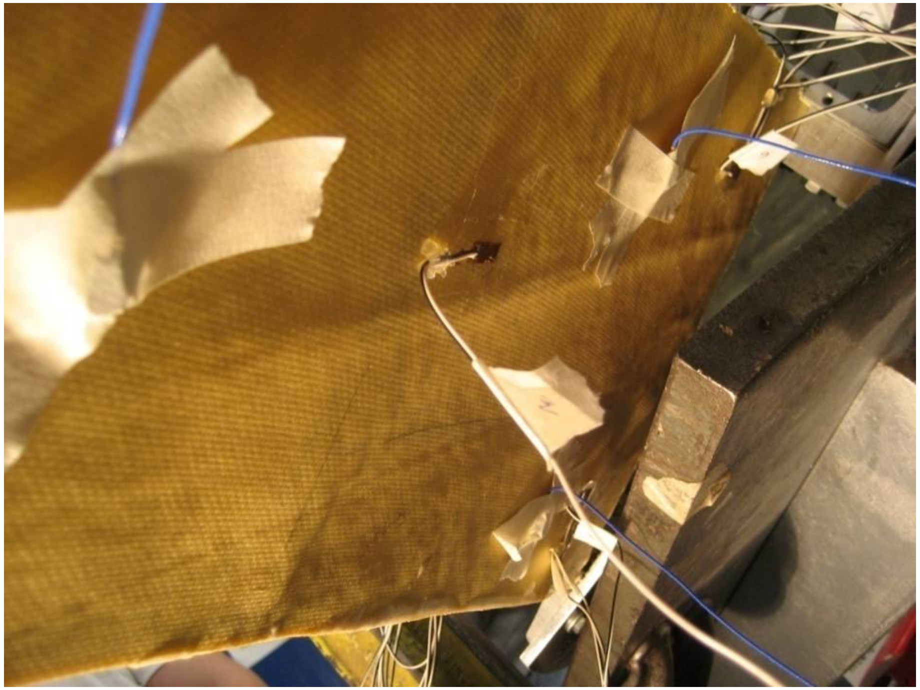


Location	Non-Structural Mass
Bulkhead One	Camera, Camera Battery, Pitot Probe
Avionics Tray between Bulkheads Two and Three	Air Retract Servo, Various batteries, Nose Gear, Air Tank and Kit, Receiver, Telemetry Transmitter, Flight Data Recorder, GPS System, Expanders and Expander Extension
Bulkheads Six and Seven	RPM sensor
Bulkheads Eight and Nine	Elevator and Rudder Servos
Engine	Engine Batteries
Wing	Aileron and Elevator Servos and Main Landing Gear

Experimental correlation with FE Predictions:
Displacement Gauges On Static Test Wingbox

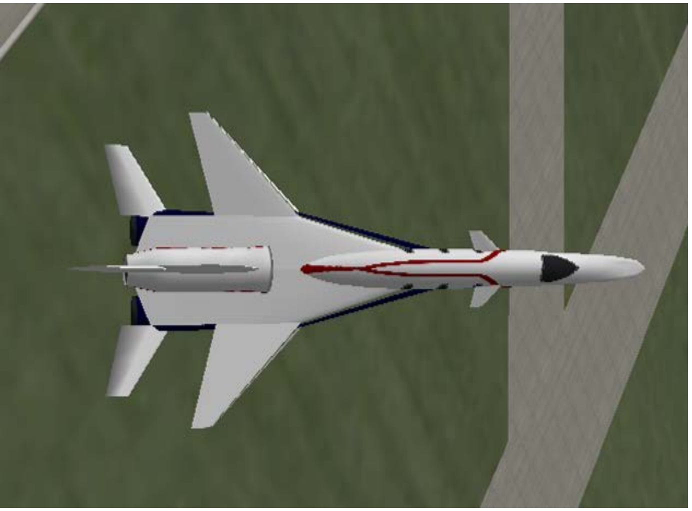


Displacement Gages on wingbox

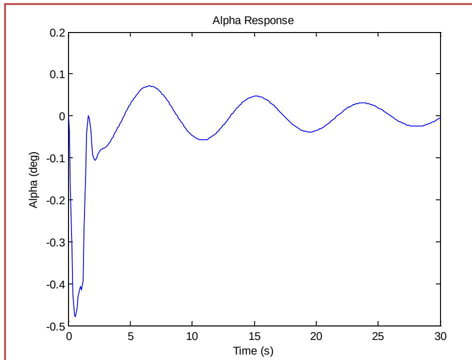


Tracking panel natural frequencies (under load) to predict panel buckling

2006 Flight Simulation Results…



V_{mu} (Airspeed to takeoff with maximum elevator and throttle)	40 mph
V_{LO} (Normal takeoff airspeed)	45mph
V_{stall} (Stall airspeed)	38 mph
V_R (Speed to rotate)	45 mph
Best climb airspeed	75 mph
Takeoff Distance	11.976 m
Takeoff Time	10.18 s
Trimmed L/D ad C_L>1.3V_{stall}	6.0863
Throttle at landing (3º glide slope)	65% of max
Throttle to maintain a 7.4º descent angle	34% of max



Phugoid

- $\omega_{phugoid}$ = 0.7321 rad
- $\zeta_{phugoid}$ = 0.0664
- Time to Half = 14.3

Dutch Roll

- $\omega_{dutch\ roll}$ = 4.8233 ra
- $\zeta_{dutch\ roll}$ = 0.1923
- Time to Half = 0.74

Short Period

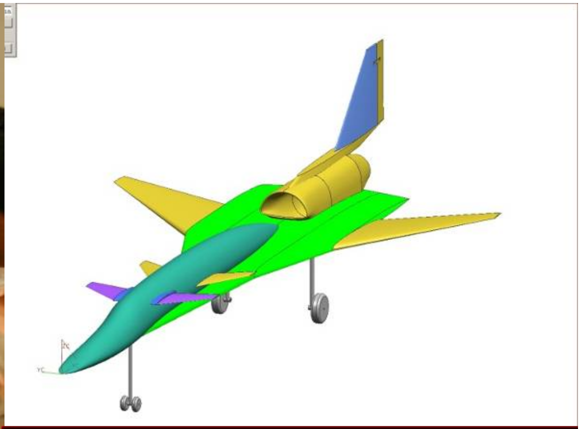
- $\omega_{short\ period}$ = 6.7528 rad/s
- $\zeta_{short\ period}$ = 0.4310
- Time to Half = 0.238 s

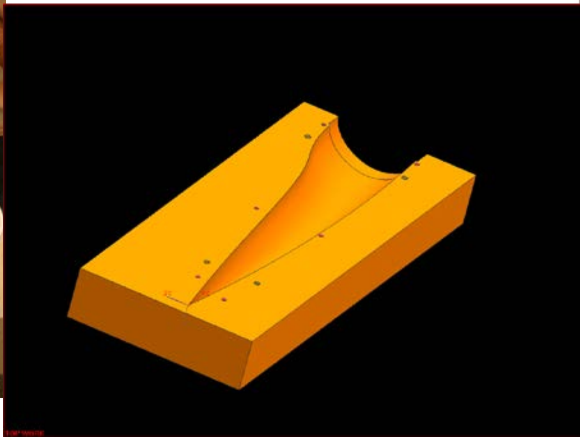
Roll Subsidence

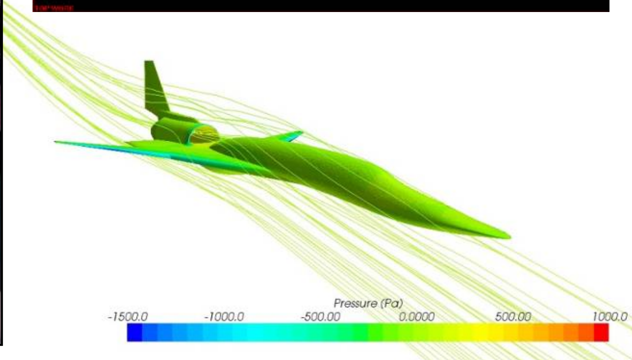
- Time to Half = 1.72 s

MatLab-based 6DOF motion analysis with, Wind Tunnel and CFD aero, was used together with piloted flight sims to predict flight characteristics.

2006 SSBJ– Completed Design.
Test Focus on Low-Speed Characteristics

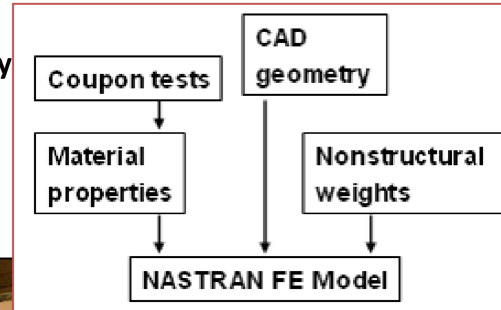


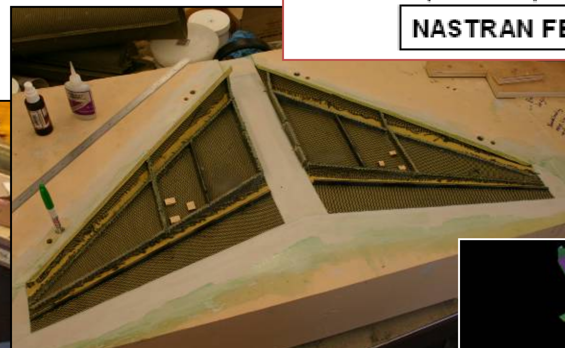


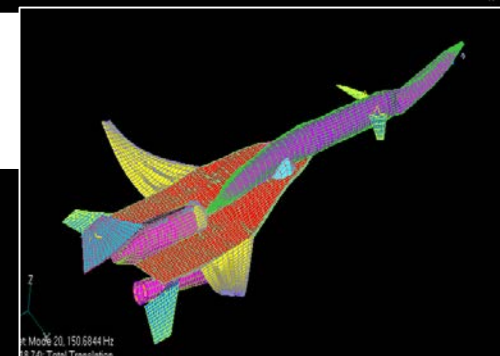


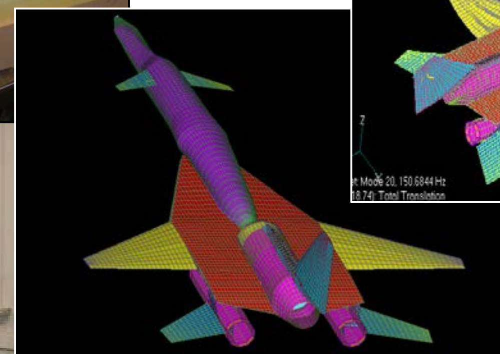
STRUCTURES:

- Epoxy/Carbon fiber/PVC sandwich & Kevlar primary structure
- Kevlar and Kevlar-Carbon hybrid skins
- Balsa core & fiberglass used on control surfaces
- Wood & Al hard-points
- Metal fittings







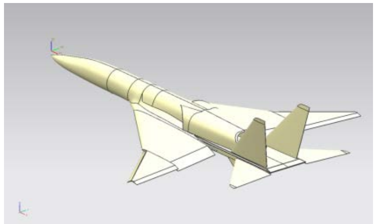


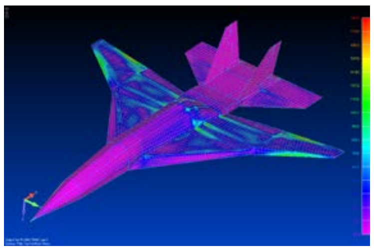
PROPULSION:

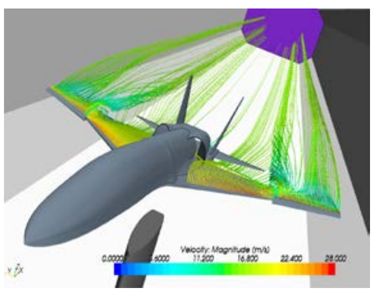
- 6.5HP EDF as " turbofan"
- Powered W.T. testing

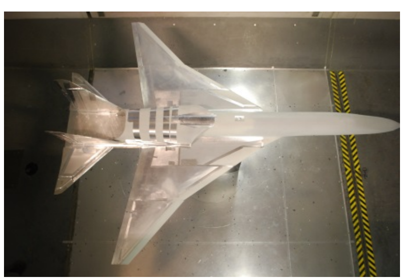
FLIGHT TEST:

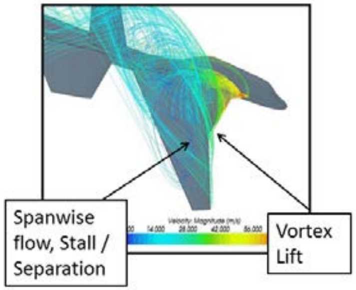
UW Capstone Design Work on Supersonic Long-Range Configurations supported by extensive CFD analysis and wind tunnel testing

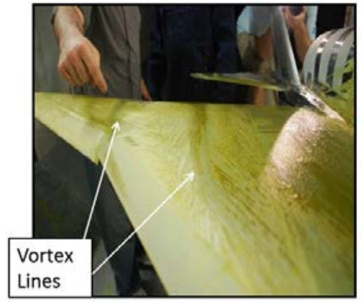


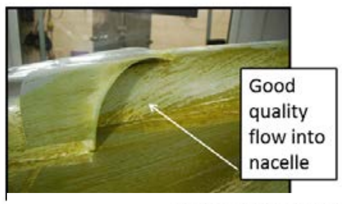


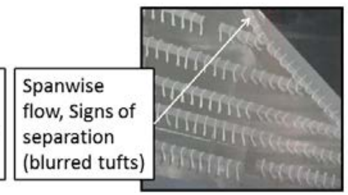




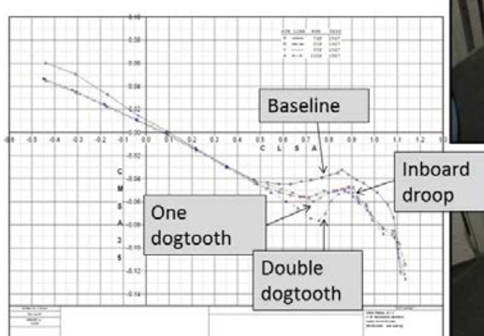


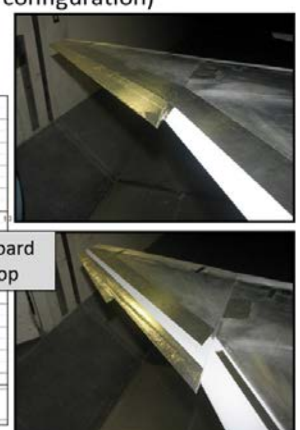






2010 UW R-UAV Pitch Stability (cM vs. cL)
Wind Tunnel Configuration Fine-Tuning Example
(not final configuration, non-optimized leading edge and wing twist, no dog-teeth used in final configuration)





2010

Contributions to Integrating U.S. Capstone Airplane Design Education and Airplane Design Research

First Challenge: Contribution to the Evolution of
Supersonic Long-Range Tailless or Reduced-Tail Configurations

A Three-Universities Effort: The University of Washington, Texas A&M, and University of Colorado

supported by the US-AFRL and AFOSR

The Key Ideas

- Advance flight vehicle design education in the U.S.
- Contribute to flight vehicles design technology in areas of interest to the AF
- Bring an flight vehicle MDO perspective and some experience to the undergraduate level
- Leverage the power of large teams of students to rapidly prototype new concepts

The Goal:
Enrich and Improve U.S. academic aircraft design education while contributing to aircraft design research
by

- Design challenges that are reflective of real challenges the aeronautics field is struggling with.
- A significant research / design education mix with valuable contributions to research as a byproduct.
- Utilization of state of the art analysis and testing capabilities and tools.
- Taking advantage of state of the art sensor, actuator, communication, control, propulsion, and materials UAV technology.
- A realistic multidisciplinary complex-systems and project organization and management experience.
- A “complete” design experience, from conceptual design to construction, ground testing, and preparation for flight tests of advanced scaled flight vehicle systems.

Considerations & Constraints

- Project's time, scope, and complexity possible in senior-year college aircraft capstone design programs.
- One-year vs. multi-year projects – undergraduate level.
- Graduate level aircraft design education.
- The international students composition and public-domain nature of U.S. university engineering programs (with consequent ITAR and export-controls constraints).
- Cost

Opportunities

- Fresh ideas. Different perspectives and contributions from the different participating universities.
-
- Low-cost fast pace design and development of new concept configurations possible by the availability of groups of students that work on such projects as part of their capstone design programs.

- A major advancement in U.S. airplane design education as well as graduate level design education by elevating the levels of difficulty, complexity, multi-disciplinary systems scope, professional analysis and testing tools required, and realism of design experience.

- Cost and schedule – research contribution possible and useful data generated at a fraction of the cost it would require by industry or government labs.

University of Washington
Capstone Airplane Design Work
on
Supersonic Long-Range Tailless or Reduced Tail Configurations

- Previous Designs

2006

- Three-surface design
- Top & bottom mounted inlets
- Electric ducted fan
- Successfully Flown

2010

- Large aft deck
- Static & dynamic stability
- Gas turbine
- Successfully Flown

The Tailless Supersonic Configuration Challenge – General Notes

- Configuration development research to date has mainly focused on the efficient cruise / low sonic boom problem.

- In the context of MDO – There has been emphasis on geometric CAD modeling for design and CFD based aerodynamic optimization.

- Supersonic configurations integrated Aeroelastic / Aeroservoelastic research to date - very limited in scope and depth partly because of the lack of design oriented integrated structural / aerodynamic / control capabilities.

- The low-speed performance, S&C, and handling qualities of supersonic configurations – Almost totally neglected in the long-range supersonic aircraft MDO work funded and published to date. High angle-of-attack / Low-speed considerations WILL affect the configuration of a supersonic long-range airplane.

- Apart from the difficulty of integrating CFD-based analysis into the supersonic configuration MDO effort, CFD technology still may not be ready for predicting high angle of attack / high sideslip angle aerodynamic behavior reliably (stall – static and dynamic , flow separation, vortex burst, shock induced separation).

The Tailless Supersonic Configuration Challenge – General Notes

- Current active control technology (unless strong flight mechanics / aeroelastic interactions occur) can be reliably used to stabilize and shape passively unstable flight dynamic behavior. A number of control law design techniques can be used, including emerging new adaptive control technology.

- For the control system required to be efficient (regarding weight, power, and complexity considerations), control effectors must be optimally integrated into a configuration to make it highly controllable at all flight & loading conditions.

- Longitudinal tailless control – more established (Concord, Tu-144, B-58, etc.)

- Directional tailless control for long-range supersonic configurations – A challenge because of the destabilizing effect of the slender fuselage, effects of forward-body cross section at high angles of attack, and potential loss of effectiveness of aerodynamic control effectors at high angles of attack and supersonic speeds due to vortex breakdown, separation, and shocks.

The Tailless Supersonic Configuration Challenge – The University of Washington Approach

Regarding aerodynamics and S&C:

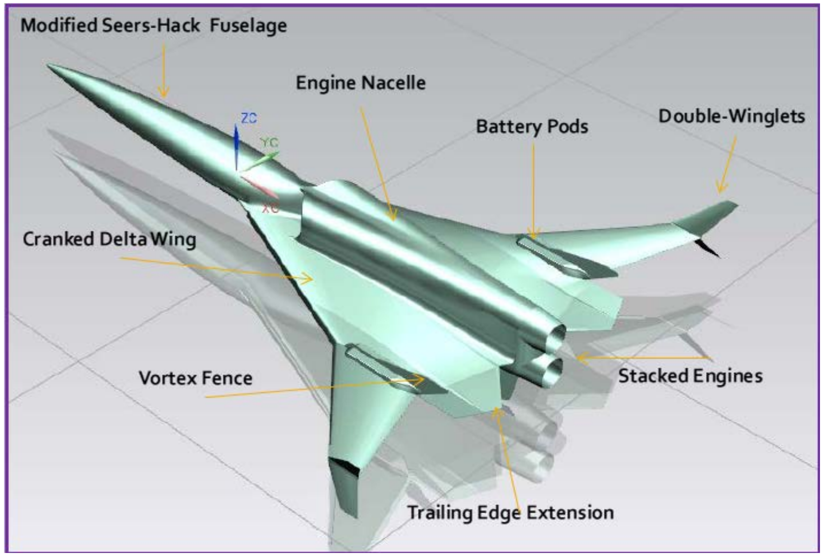
- Emphasis on the understanding of the aerodynamic and S&C issues involved and developing a configuration that is mission-efficient and efficiently-controllable.
- CFD driven configuration shaping accounting for both high-speed and low-speed.
- Commercial quality low-speed wind tunnel testing to fine-tune the configuration for good performance at low and high angles of attack and sideslip angles, fine tuning and validating CFD modeling, direct measurement of control effectors effects.
- Utilization of a hierarchy of modeling methods: handbook methods, panel codes, CFD codes, and wind tunnel test results and evaluating consistencies and differences.
- Creation of wind-tunnel based / CFD based / panel code based flight mechanics state-space models.
- S&C dynamic behavior studies using resulting Matlab state-space models and commercial software simulator X-plane.
- Evaluate alternative configurations and alternative control effectors.
- Effectiveness of control effectors can be studied, with typical long-range supersonic configurations, on longitudinally and directionally stable configurations before tails are reduced or taken-off completely. The UW designs allow for “shrinking” tail surface – from full size to no-tails.

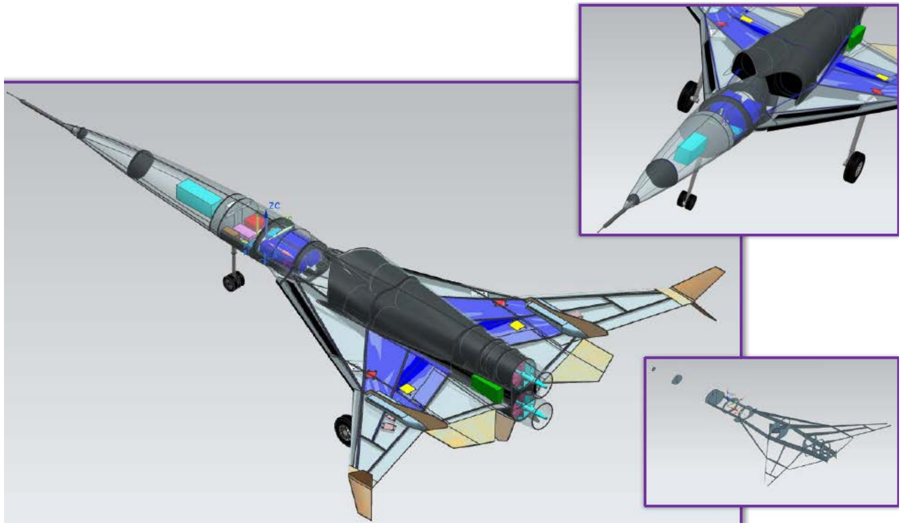
“Adapting” the design challenge to a public-domain university environment

- Design a tailless or minimal-tail civil airplane that would carry a certain payload over a certain range.
- With common “numbers” of interest currently in the supersonic business jet area: 10 passengers + two crew members with a range of 4500 miles at Mach 1.8.
- The specific payload and range can, of course, be revised to study any mission.

- The design effort begins with the conceptual design and sizing of the full vehicle.
- The design is then scaled down to Research UAV (R-UAV) scale, followed by detail-design, ground tests, construction, and flight tests.

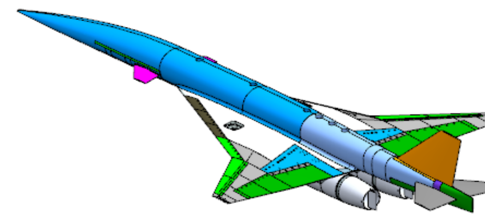
2013 UW RUAV





- Various wing control surfaces & their effects
- Wingtip rudders
- A unique airframe / propulsion system integration concept

Previous Designs



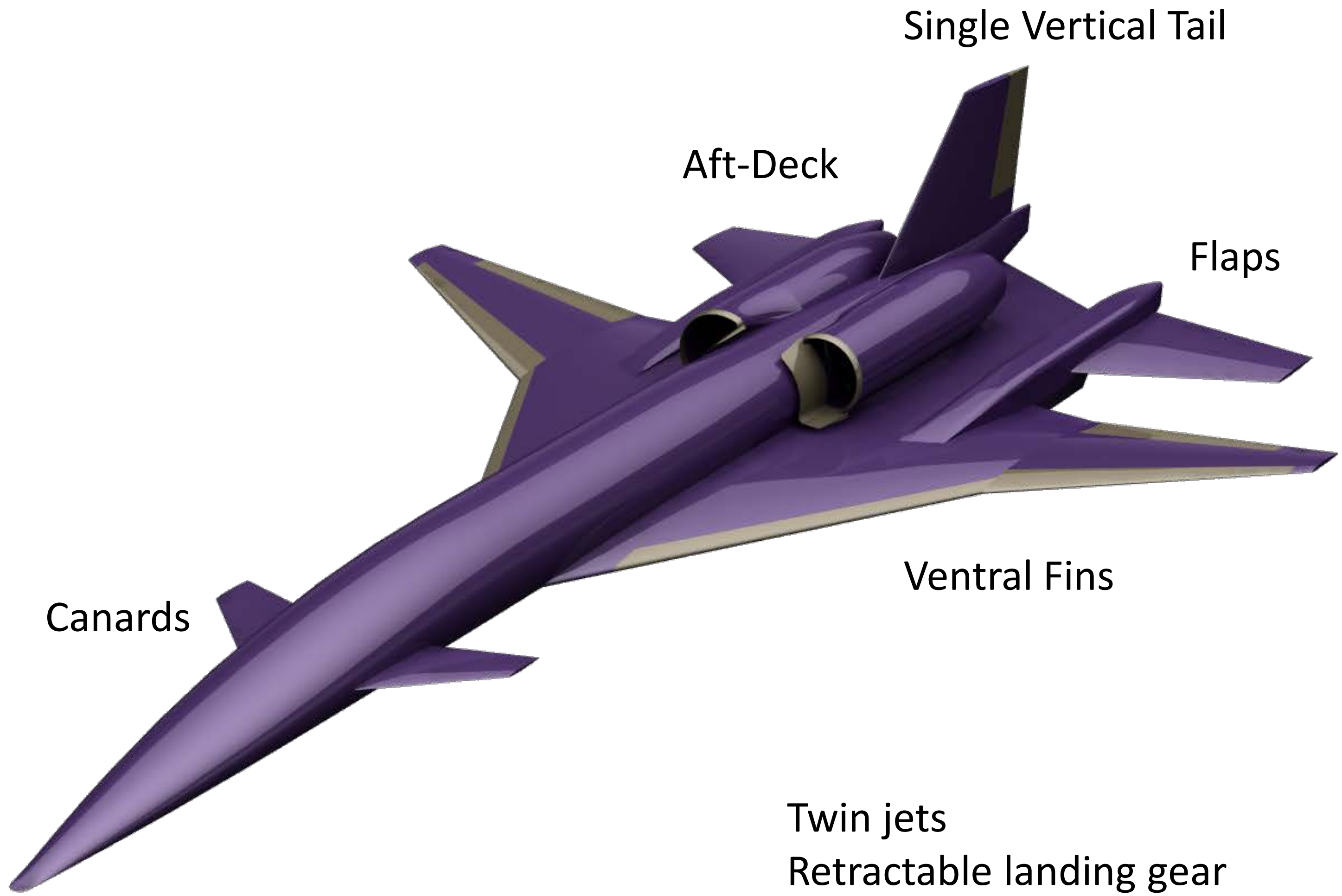
2014

- Tailless supersonic configuration
- Underwing engines
- Dihedral canard & complex control surfaces
- Modular vertical tail that can be completely removed.

2015

- Three-surface supersonic design
- Underwing engines
- Vectored thrust for reduced vertical tail

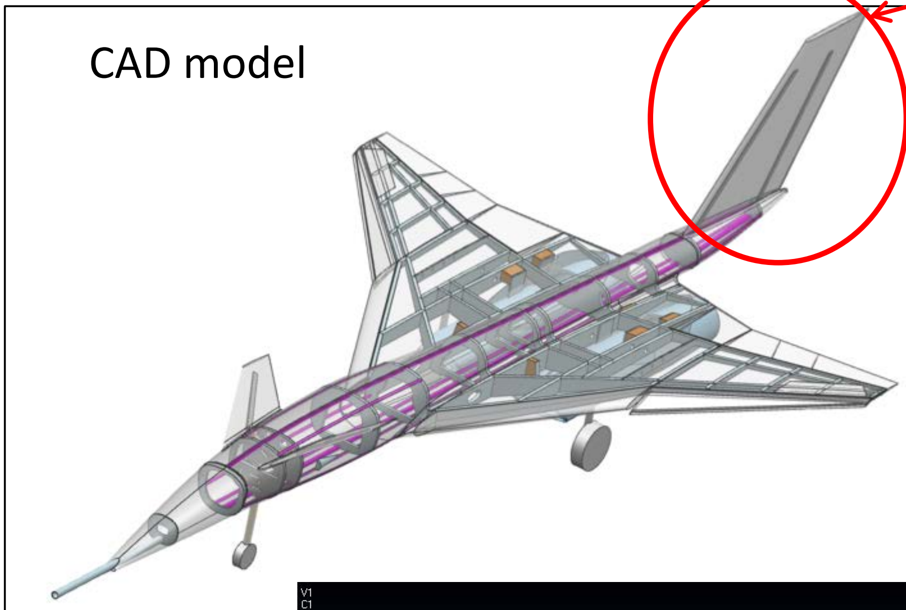
- 2016 UW RUAV

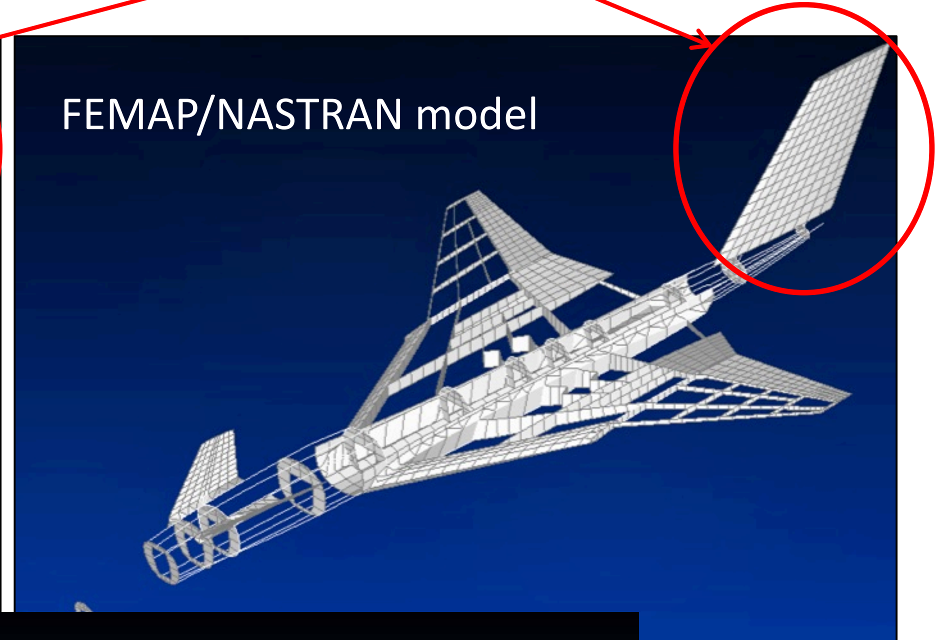


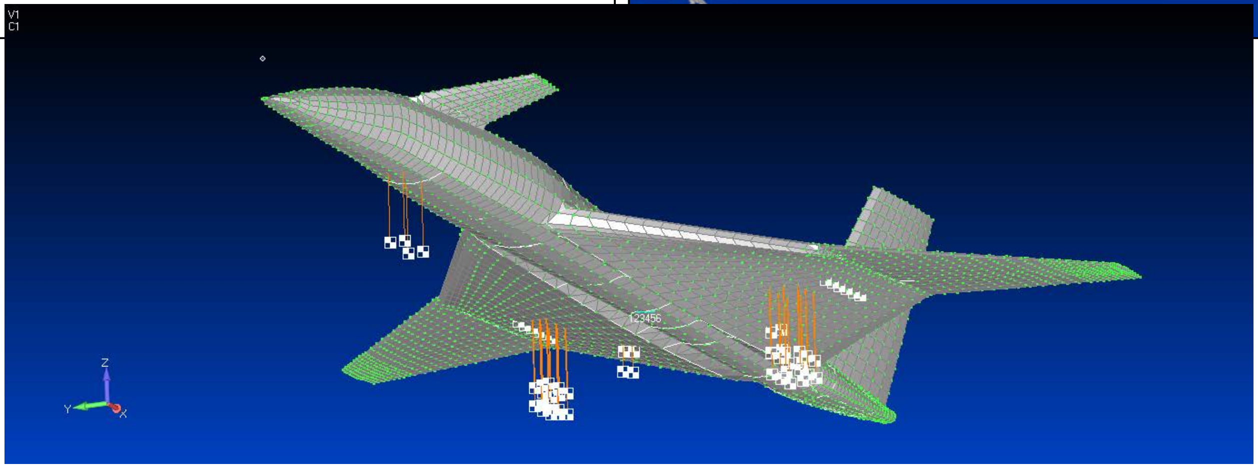
Twin jets
Retractable landing gear
All control surfaces – moving
Advanced flight test instrumentation

2014 UW R-UAV – Structural Model

largest size vertical tail shown



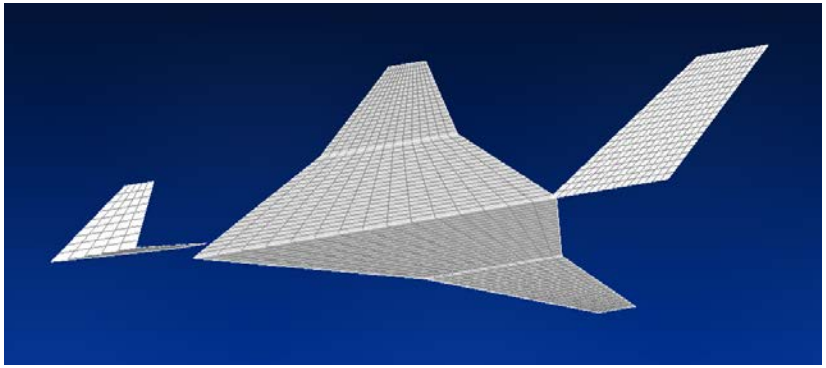




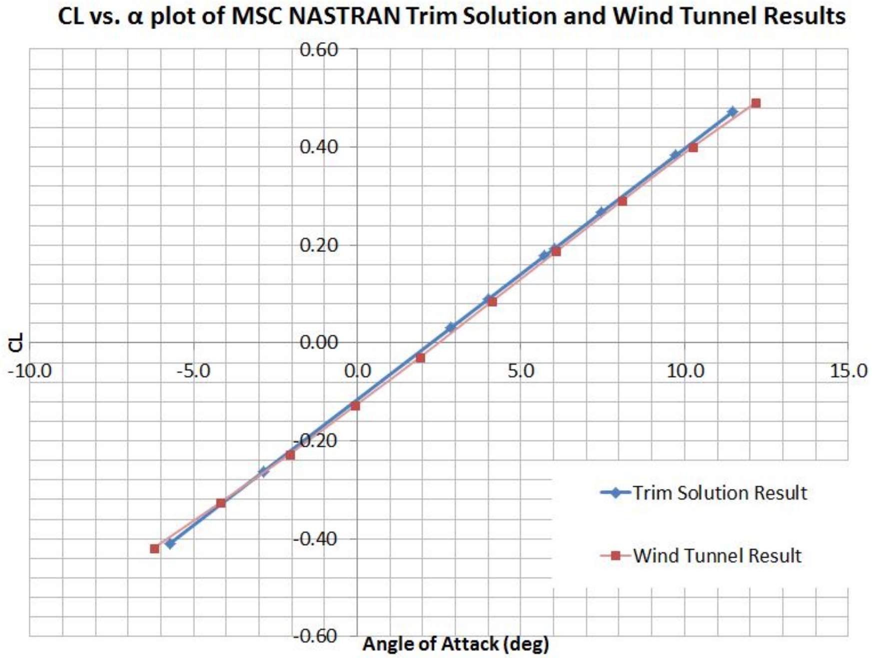
WILLIAM E. BOEING DEPARTMENT OF AERONAUTICS & ASTRONAUTICS
UNIVERSITY of WASHINGTON

Flutter and Trim Analysis

- MSC NASTRAN
- Aerodynamic doublet mesh formation
- Canards modeled as rigid
  - Analyzed separately to account for spring stiffness
- Mach = 0 aerodynamics
- Full UAV model flutter speed is 511 mph
  - High stiffness and low weight
- Cantilevered wing flutter speed is 2272 mph
- Flutter testing void, large margins of safety
- Very stiff structure
  - Aeroelastic trim solutions converge with "rigid" results from wind tunnel



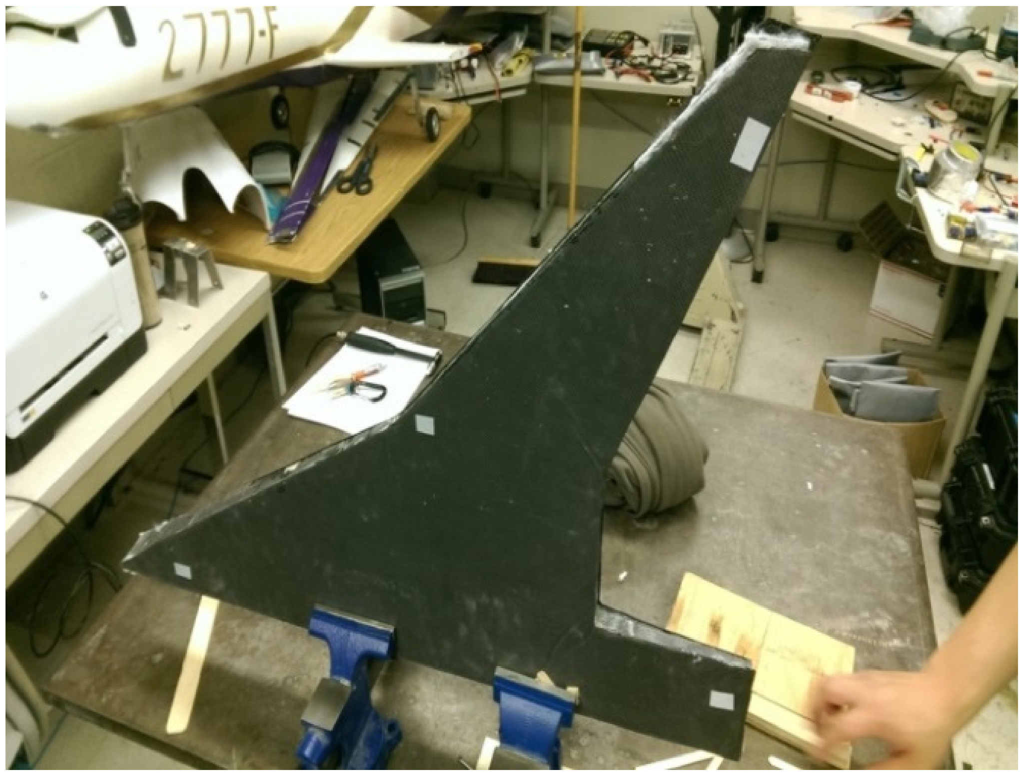
Aerodynamic mesh used for flutter analysis



WILLIAM E. BOEING DEPARTMENT OF AERONAUTICS & ASTRONAUTICS
UNIVERSITY of WASHINGTON

Prototype wing

- Built for NASTRAN Finite Element model validation and loads test to failure

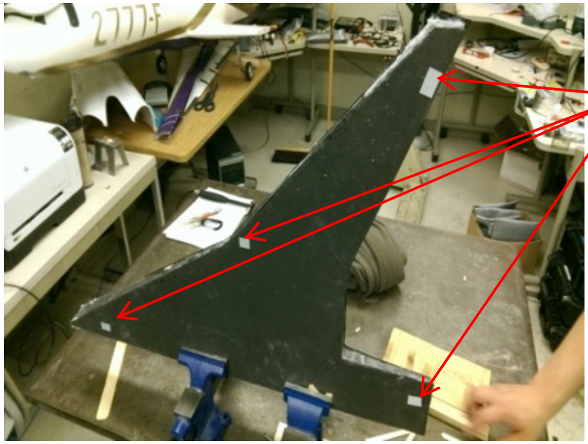


Ground Vibration Tests

Building Confidence in Airframe Structural Dynamic Modeling

- Ground Vibration Testing (GVT)
  - Excite modes by tapping load cell hammer in different places on wing
  - Laser vibrometer measures velocities at various wing skin locations
- Matched FEMAP/NASTRAN modes to within 10%

May 14 2015

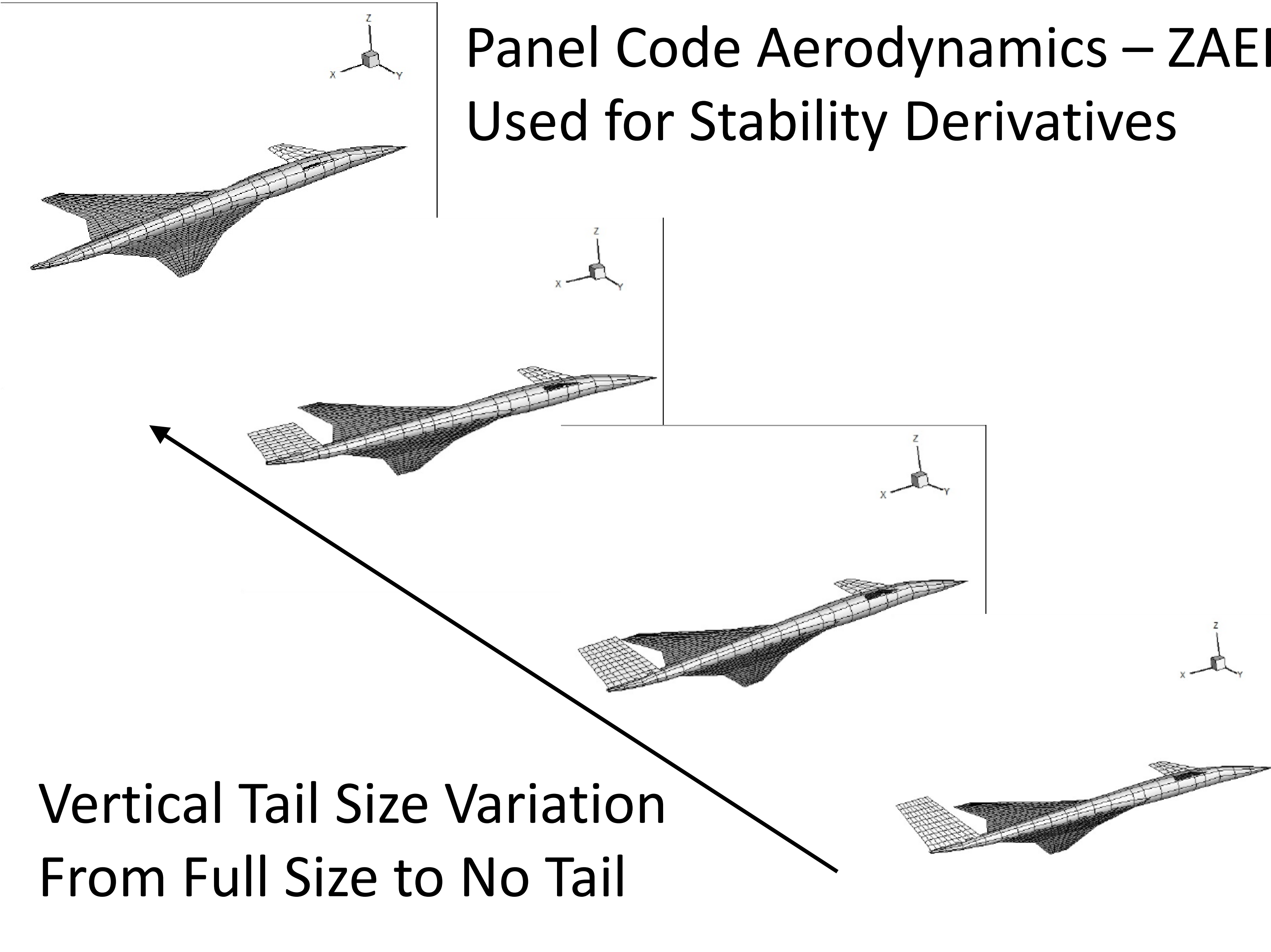


Reflective tape for laser vibrometer measurements

GVT setup

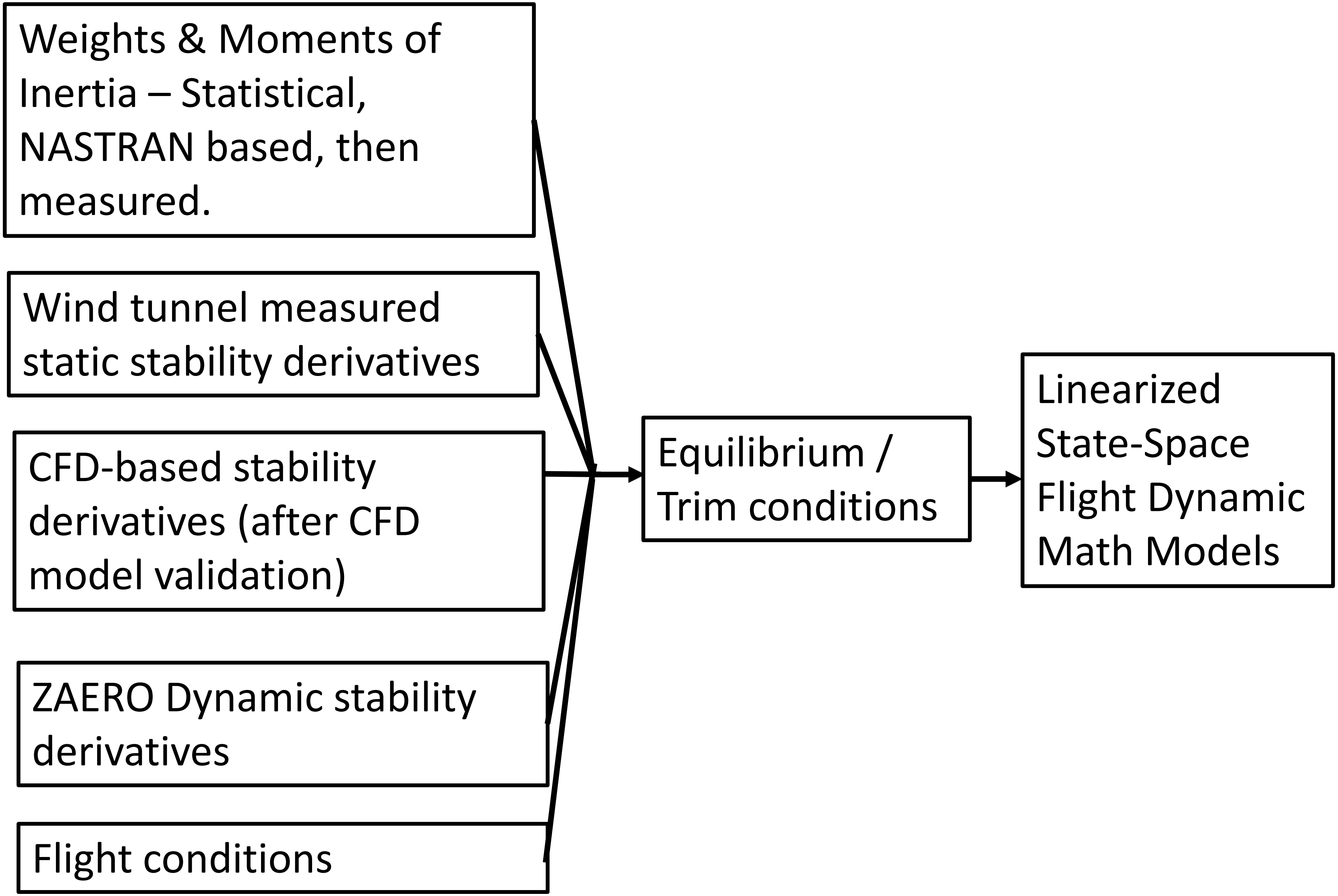
Mode	GVT results	FEMAP results
1	86 Hz	88 Hz
2	235 Hz	270 Hz
3	361 Hz	318 Hz
4	401 Hz	447 Hz

Panel Code Aerodynamics – ZAERO Used for Stability Derivatives



Vertical Tail Size Variation
From Full Size to No Tail

WILLIAM E. BOEING DEPARTMENT OF AERONAUTICS & ASTRONAUTICS
UNIVERSITY of WASHINGTON


Weights & Moments of Inertia – Statistical, NASTRAN based, then measured.
Wind tunnel measured static stability derivatives
CFD-based stability derivatives (after CFD model validation)
ZAERO Dynamic stability derivatives
Flight conditions
Equilibrium / Trim conditions
Linearized State-Space Flight Dynamic Math Models

Sarah Langston's MSAA Thesis

- Guide construction and instrumentation of the 2014 UW R-UAV.
- Use wind tunnel results, CFD, and panel code dynamic derivatives as well as up to date inertial property data to create linear Time Invariant (LTI) MIMO state space models of the 2014 R-UAV flight dynamics at small and high angles of attack.
- Study controllability in all axes.
- Identify more efficient and less efficient control effectors.
- Use active controls in an exploratory study to evaluate simple rate-gyro based control and LQR.
- Study the level of activity of all control surfaces used in the closed-loop designs.

Development along the lines discussed above, with AF support, began at Texas A&M and at the University of Colorado in 2013.

The Texas A&M and U Colorado program development began much later than that of the University of Washington, hence the more preliminary nature of those programs.

The Texas A&M Work
Professors John Valasek and Tom Strganac

Tasks

Task 1. Identify key technical challenges

Task 2. Highlight shortcomings and limitations in public domain aerodynamic and aeroelasticity tools.

Task 3. Propose solutions to the items listed in Task 1 and Task 2.

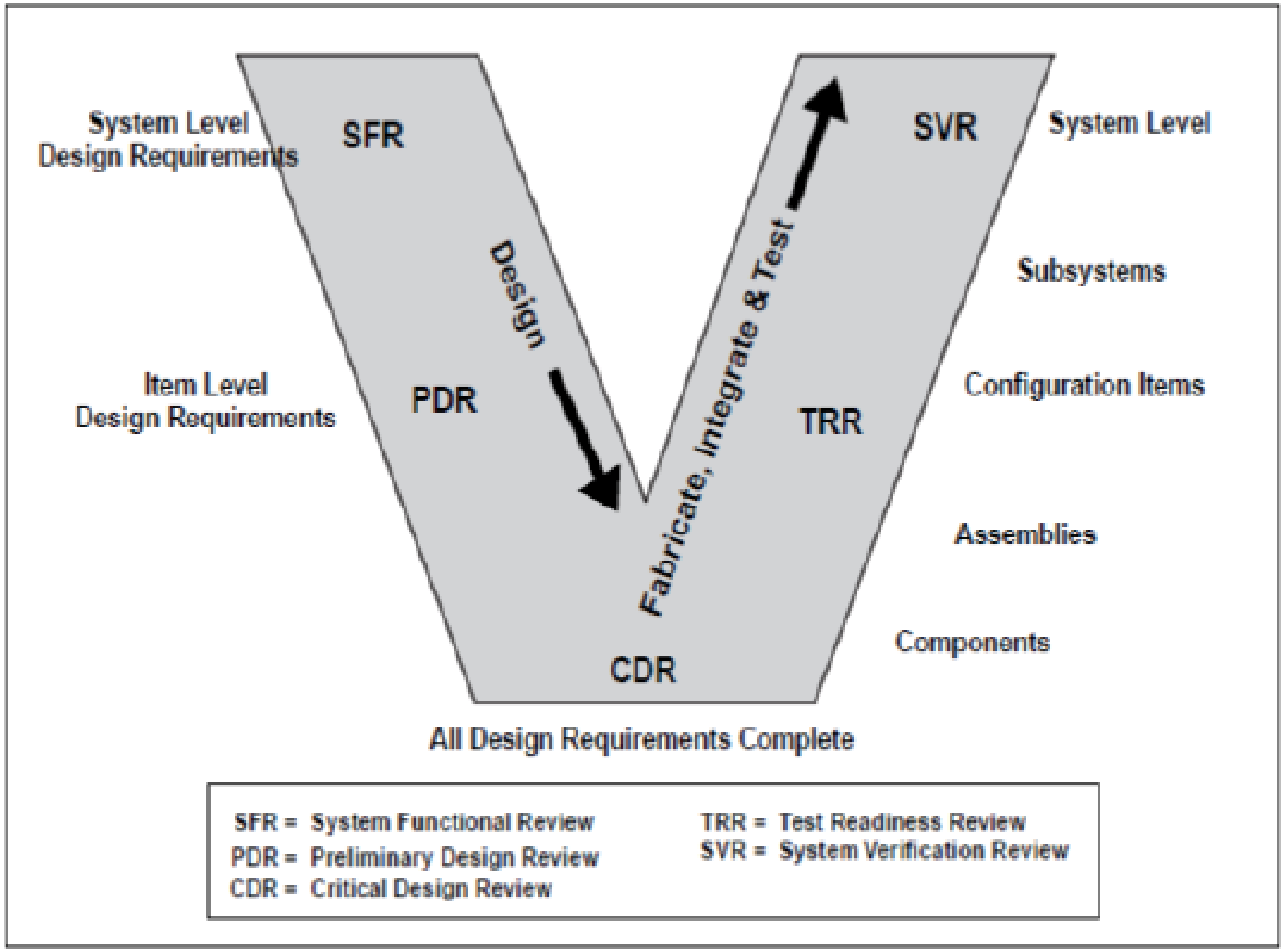
Task 4. Synthesize a preliminary design of a supersonic tailless aircraft, based on general guidelines learned from past work.

Task 5. Build and fly sub-scale low speed demonstrator of the design from Task 4. Collect and analyze flight data.

Task 6. Document and present results.

Objectives

- Enhance the undergraduate student experience by learning and applying the systems engineering approach to specifying, defining, and creating complex engineering systems.
- Foster the learning and development of real-time software development skills and aviation human factors.
- Learn to work effectively on a team to meet realistic deadlines and deliverables.



Systems engineering design process used in AERO 401, AERO 402, and AERO 440

AA401 & AA402: aircraft senior capstone design
AA440: Cockpit systems and displays

Supersonic Tailless Aircraft

- Simulation Tools:
  - Advanced Airplane Analysis – AAA by DARcorp
  - CAD: Solidworks
  - FE: Abaqus & GRAPE 3D
  - Aero: TRANS3DNS, VLLOFT, VLLAMAR, HESSVNN, DBLDLTN/DBLDLTL, ZEBRA2, TRANSDESN.

Design Phases

- 1. Concept development and conceptual design
- 2. Real time flight simulation for S&C evaluation
- 3. Full or sub-scale flight model
- 4. Wind tunnel tests of the flight model
- 5. Flight tests

Texas A&M Wind Tunnel Tests

Figure 2. Supersonic aircraft demonstrator attached to mothership

Figure 3. Supersonic aircraft demonstrator attached to mothership undergoing flow visualization via smoke

Flight Tests

- The vehicle is longitudinally unstable
- Active control development is required

Systems Engineering Aspects at Texas A&M

- Cockpit Systems & Displays AERO 440 used to improve systems engineering content in aerospace design courses.
- Students teams: mixed aerospace & computer science.
- Design and build ground stations for Texas A&M-designed UAVs.
- Cover the full process of design and development of aerospace systems and their engineering management.

University of Colorado
Professor Ryan Starkey

Integrated Research and Education in Airplane Design

- Began as GOJETT (Graduate Organization Jet Engine Technology Team) in Fall 2009
  - Goal of designing a turbojet for RC hobby use
- In Fall 2010, grew to a full UAV project based around that engine
  - Set goals of breaking UAV speed world record for under 50kg
  - Supersonic UAV that could become a test bed for supersonic flight

The University of Colorado’s 2015 GOJETT team

- The plan was to add significant undergraduate capstone design participation in this project and then expand undergrad capstone design scope and depth to cover other designs.

- A progress report for 2015-2016 has not been received yet.

Additional Notes – The Benefits of Designing, Building, and Testing Many Concept Prototypes

- http://aviationweek.com/defense/dassault-panoply-fighter-prototypes#slide-0-field_images-1300091

- A Quote: "Dozens of prototypes built and flown over decades have given Dassault an ability to design advanced combat aircraft that belies the company's relatively small size for a defense contractor."

- The University of Washington, Texas A&M, and University of Colorado View: Active configuration development / low-cost and fast UAV prototype development by U.S. academic airplane design programs, while not working with full size vehicles, enrich U.S. aircraft design information archives and U.S. configuration design experience.

Discussion

- Advancing airplane capstone design education at the undergraduate level
- Advancing MDO at the undergraduate level
- Building integrated undergraduate / graduate level programs in which graduate level research continues with the vehicles designed and built by the capstone undergraduate design teams
- Funding airplane design education at the graduate level
- The power of large student teams in rapid prototyping of innovative concepts
- The importance of design and rapid construction and tests of innovative configurations
- Areas of interest for the USAF
- Benefits for the USAF: education of future leaders in flight vehicle technology and operation, design innovation, results of design studies and associated research, results of tests (ground and flight) that can be used to validate AF design tools development

Additional Important Notes on Supersonic Tailless Design

- Optimization algorithms tend to find the weakness in the mathematical models involved that would lead to poor results.
- For MDO of supersonic long-range configurations aerodynamic performance and S&C models must be accurate and reliable at all flight conditions.
- For maneuvering and for T/O and landing the high AOA / high-Beta aerodynamics of slender supersonic configurations must be well understood, and CFD models must be solidly fine-tuned and validated.
- Aerorelastic modeling and aeroelastic optimization are less of a technical challenge today, but for such MDO work to be viable accurate and reliable FE models and unsteady aerodynamic models must be available.
- Areas that need major R&D work:
  - Stability Augmentation – Gust Alleviation – Active Flutter Suppression of highly deformable aircraft with multiple flutter mechanisms.
  - Aeroservoelastic optimization,
  - Reliability and Uncertainty analysis,
  - Flight dynamics of the highly deformable airplane,
  - Aerothermoelasticity (if Mach numbers are high).