Multidisciplinary Optimization of Innovative Aircraft using ModelCenter

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Rakesh K. Kapania

Mitchell Professor

And

Joseph A. Schetz

Durham Chair in Engineering

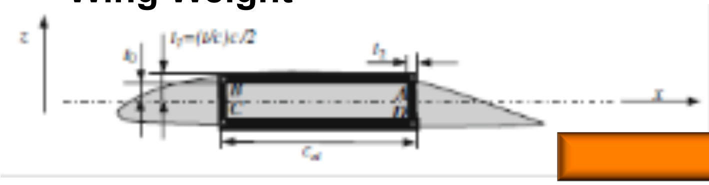
Department of Aerospace & Ocean Engineering

General Framework

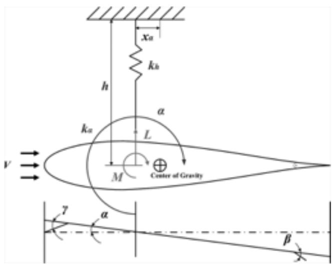
Physics Based Analysis

New Aircraft Concepts Analysis

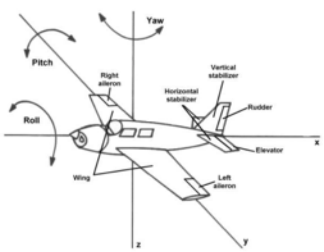
Wing Weight



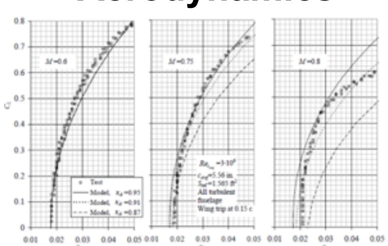
Flutter

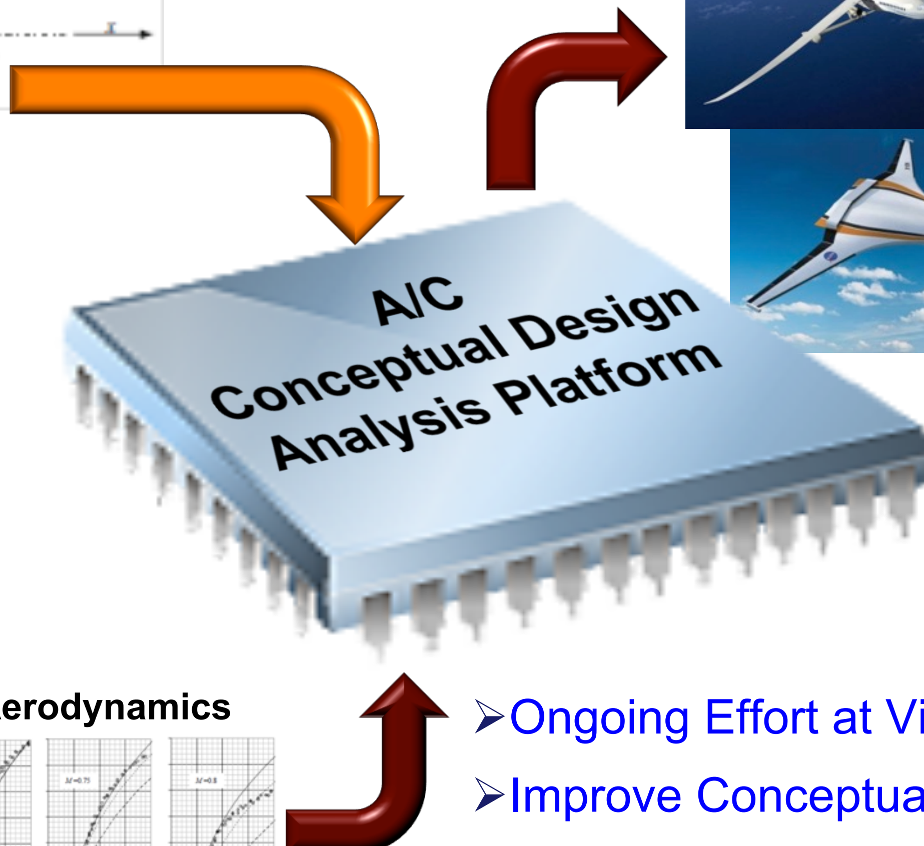


Control/Stability



Aerodynamics





- ➢Ongoing Effort at Virginia Tech
- ➢Improve Conceptual Design Analysis
- ➢Extend Analysis to Non-Conventional Configuration

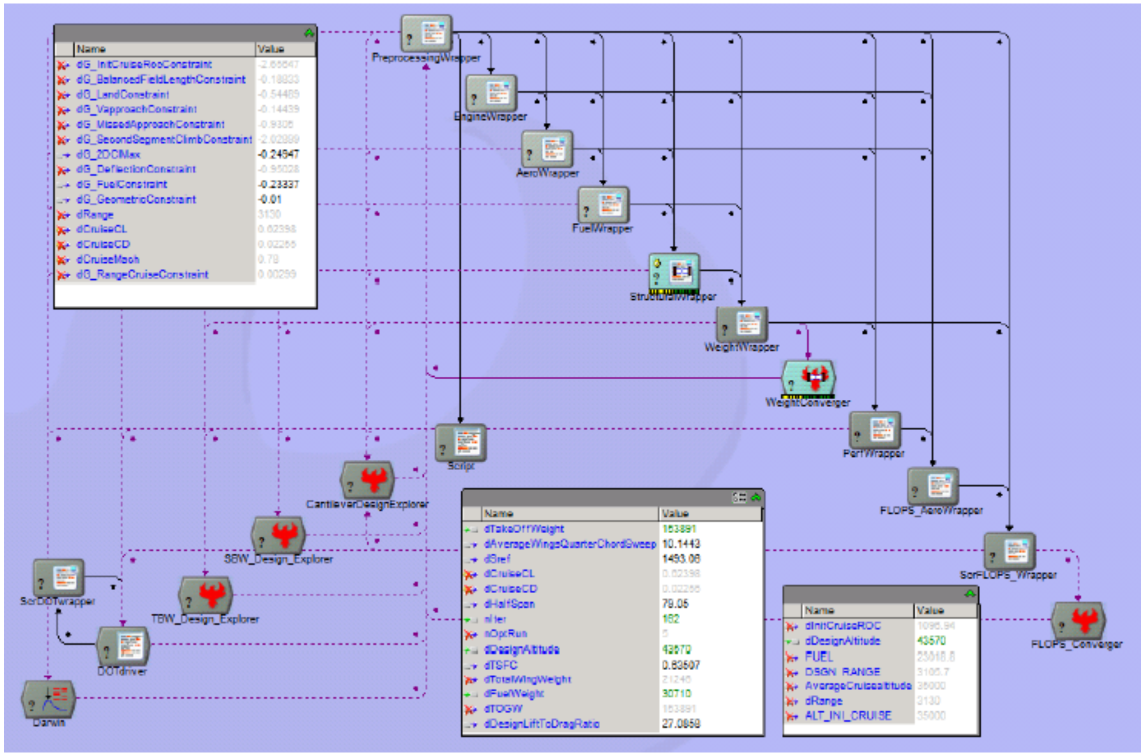
Overview

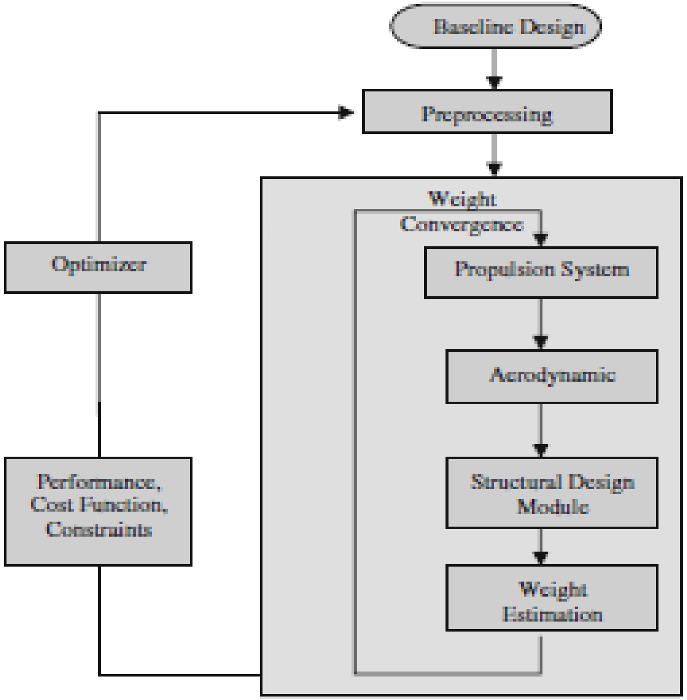
- Multidisciplinary Optimization (MDO) Tool at Virginia Tech
  - Developed over the past two decades

- Application
  - Truss-braced wing (TBW) aircraft MDO research
    - Earlier results – huge benefits of TBW to fuel burn and TOGW reduction as observed through MDO studies
    - Effect of flutter constraint in MDO studies of TBW
    - Aeroelastic benefits of a Novel Control Effector to TBW via a MDO study
    - Preliminary stages of current MDO research for SUGAR III TBW aircraft
  - Tailless supersonic aircraft MDO research

TBW MDO research

VT MDO Framework



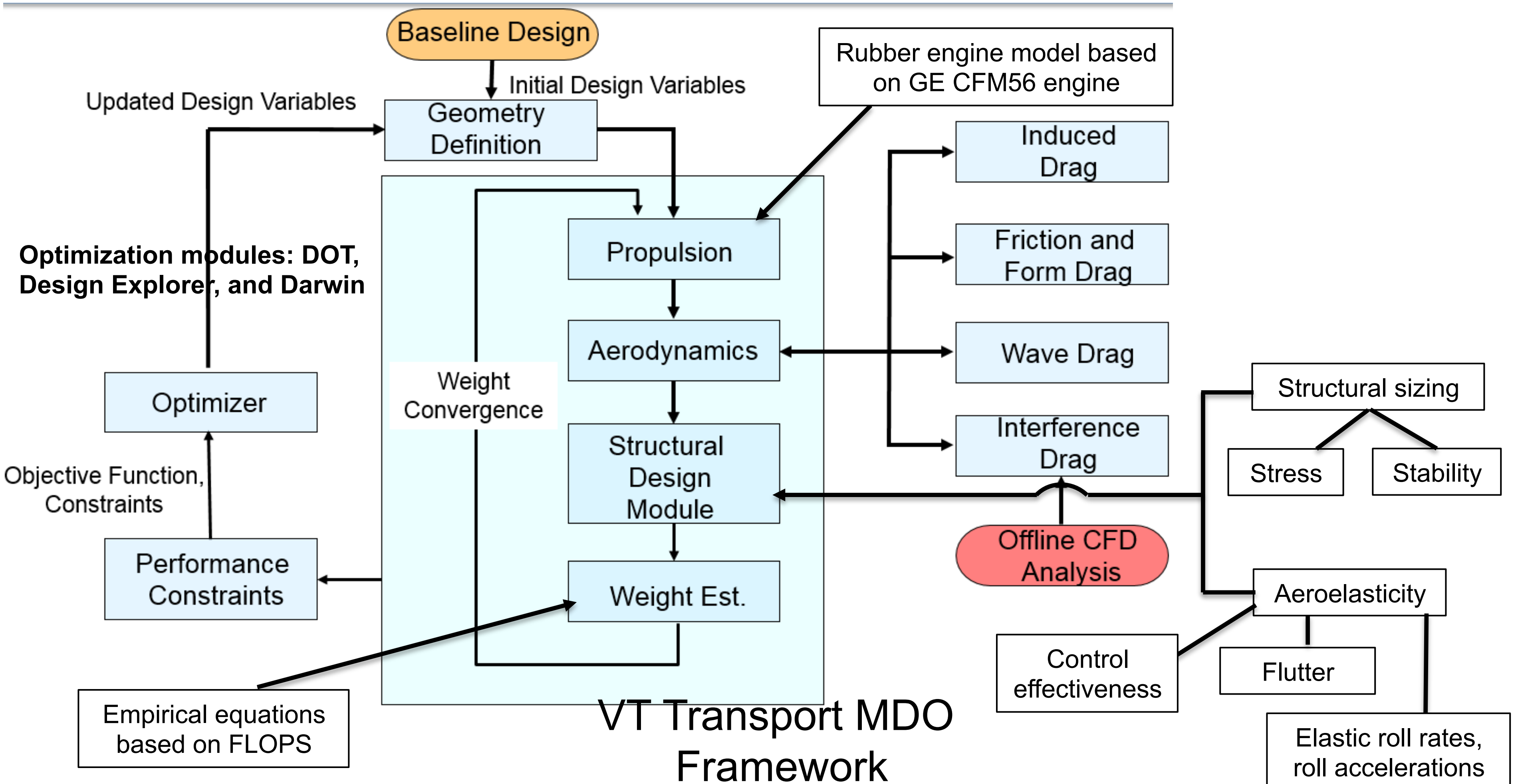


- Product of Two Decades Effort
- Analysis Platform: ModelCenter + FLOPS
  - ModelCenter: Connects Analysis Modules, Provides Optimization Algorithms
  - FLOPS: Provides Analysis Methods (Empirical)

- Double Loop Architecture:
  - TOGW Computation
  - Performance Optimization
- Application
  - Conventional
  - SBW and TBW

MDO Framework

- Use Multidisciplinary Design Optimization (MDO) to explore the potential for LARGE improvements in subsonic, transport aircraft performance by employing truss-braced wings combined with other advanced technologies.



Design Load Cases

Load Case	Load Case Type	Fuel (%)	Altitude (kft.)
1	+2.5g	100	40
2	+2.5g	50	40
3	-1.0g	100	40
4	-1.0g	50	40
5	2.0g Taxi Bump	100	-
6	Gust (V_{app})	100	0
7	Gust (V_{app})	0	0
8	Gust	100	0
9	Gust	0	0
10	Gust	100	10
11	Gust	0	10
12	Gust	100	20
13	Gust	0	20
14	Gust	100	30
15	Gust	0	30
16	Gust	100	40
17	Gust	0	40

Design Variables

#	Design Variables	Cantilever	SBW	TBW
1	Fuel Weight	✓	✓	✓
2	Max Required Thrust	✓	✓	✓
3	Design Altitude	✓	✓	✓
4	Wing Tip X co-ordinate	✓	✓	✓
5	Fuselage Strut Joint		✓	✓
6	Jury-Wing Joint			✓
7	Wing- Strut Joint		✓	✓
8	Jury- Strut Joint			✓
9	Offset Length		✓	✓
10	Wing Span	✓	✓	✓
11	Root Chord Thickness	✓	✓	✓
12	Tip Chord Thickness	✓	✓	✓
13	Strut Thickness at Wing Intersection		✓	✓
14	Strut Thickness at Fuselage Intersection		✓	✓
15	Strut Thickness at Intersection with Jury			✓
16	Root Chord Length	✓	✓	✓
17	Tip Chord Length	✓	✓	✓
18	Strut Chord Length at Wing Intersection		✓	✓
19	Strut Chord Length at Fuselage Intersection		✓	✓
20	Strut Chord Thickness at intersection with Jury			✓
21	Jury Chord Length			✓

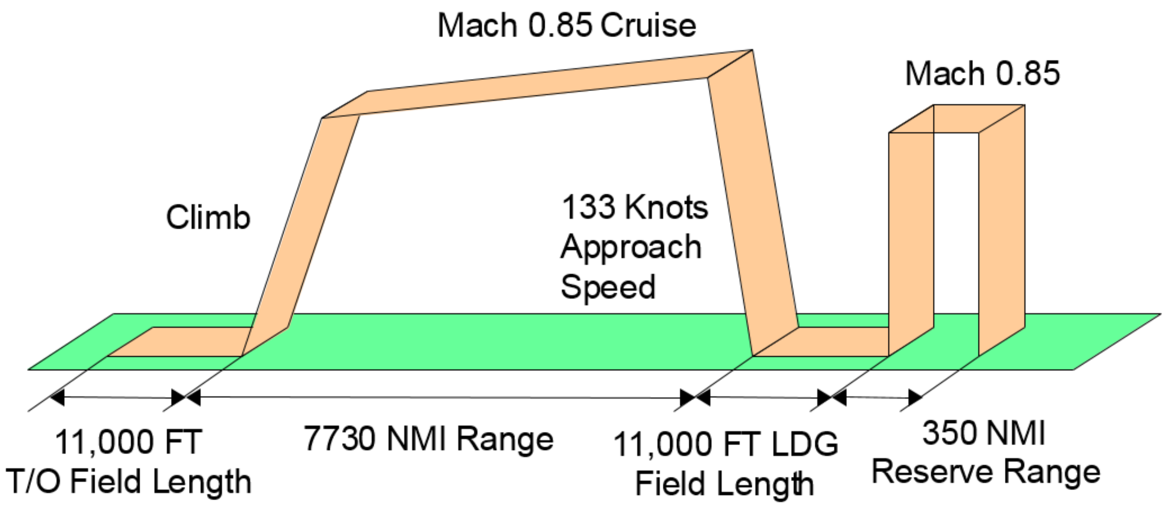
Non-geometric Design variables

Geometric Design variables

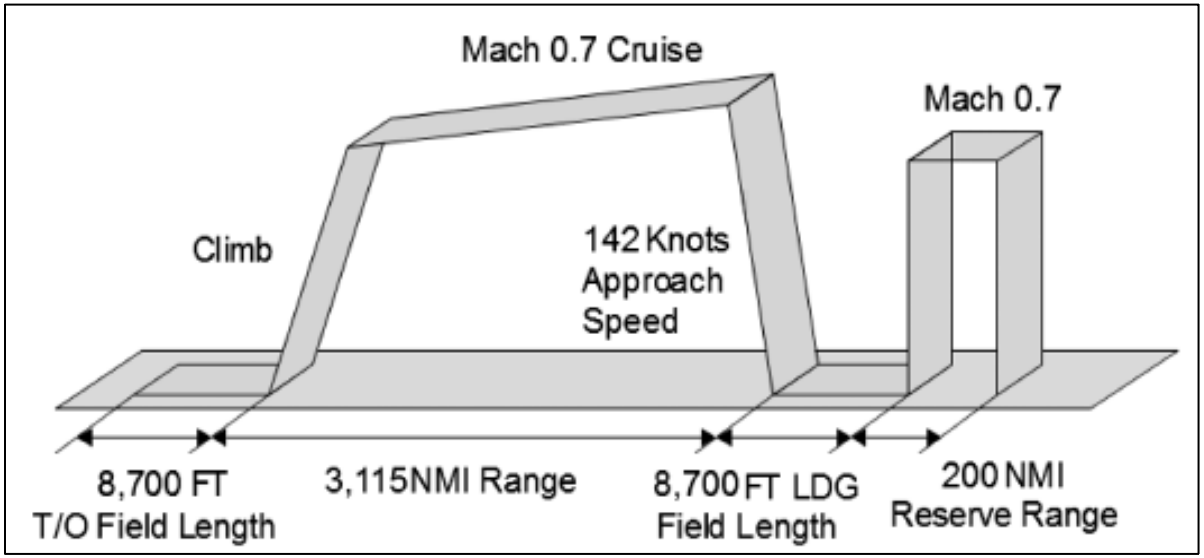
Constraints

- Range ≥ 7730 [NM] + 350 [NM] (reserve)/3115 [NM] + 200 [NM] (reserve)
- Initial Cruise ROC ≥ 500 [ft/min]
- Max. C_l (2-D) ≤ 0.8
- Available fuel volume ≥ required fuel volume
- Wing tip deflection ≤ 20.3 [ft.] (fuse. diameter)
- 2^{nd} segment climb gradient (TO) ≥ 2.4% (FAR)
- Missed approach climb gradient ≥ 2.1% (FAR)
- Approach velocity ≤ 132.5 [kn.]
- Balanced field length (TO & Land.) ≤ 11,000 [ft.]/ 8,700 [ft.]
- Flutter speed ≥ Flutter boundary
- Roll rate, roll acceleration ≥ required values for projected banking motion in roll

Flight Mission of Transport Vehicle



235-passenger, 7730 NM range, Mach 0.85 dual-aisle transport aircraft (similar to 777)



162-passenger, 3115 NM range, Mach 0.70 single-aisle transport aircraft (similar to 737)

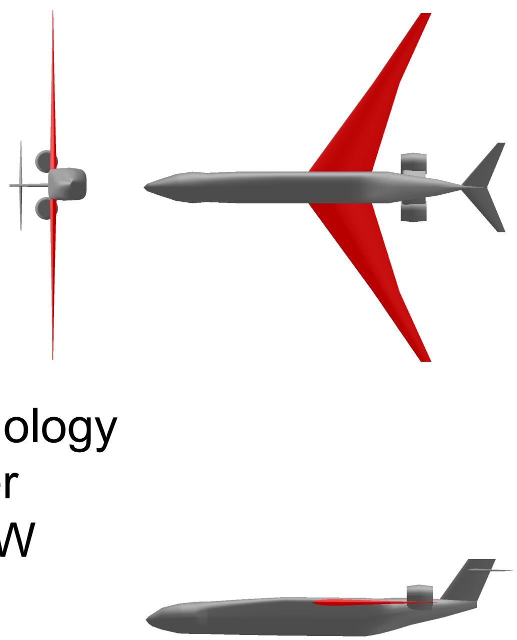
Earlier TBW MDO research

TBW Study Matrix

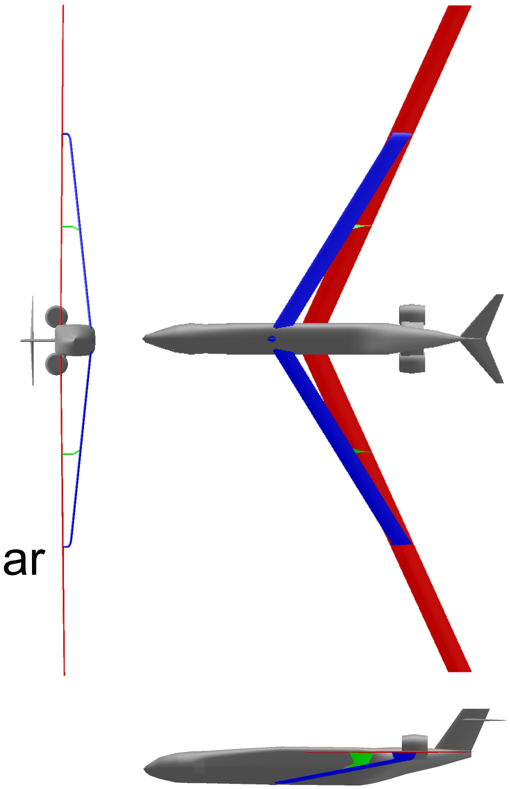
- Configurations:
  - Cantilever wing
  - Single member TBW: SBW
  - Three members TBW: Jury TBW
- Current Design goals:
  - Min. TOGW
  - **Min. Fuel Weight and Emissions**
  - Max. L/D
- 2 Friction drag cases:
  - Aggressive laminar:
    Wing Technology Factor =1 (F-14 Glove exp.)
    Fuselage: riblets and “Flat Plate” Transition $Re_x=2.5\cdot10^6$
  - Current technology:
    Wing Technology Factor =0 (Current wings)
    Fuselage: No riblets and “Flat Plate” Transition $Re_x=0.25\cdot10^6$

Cross Comparison – Long-range Mission "777-like"

- 2% Higher TOGW with 32% less fuel (57[klb] saved fuel weight)
- 112[ft] vs. 214[ft] half span
- 76[klb] vs. 133[klb] wing weight



Current Technology
Cantilever
Min. TOGW



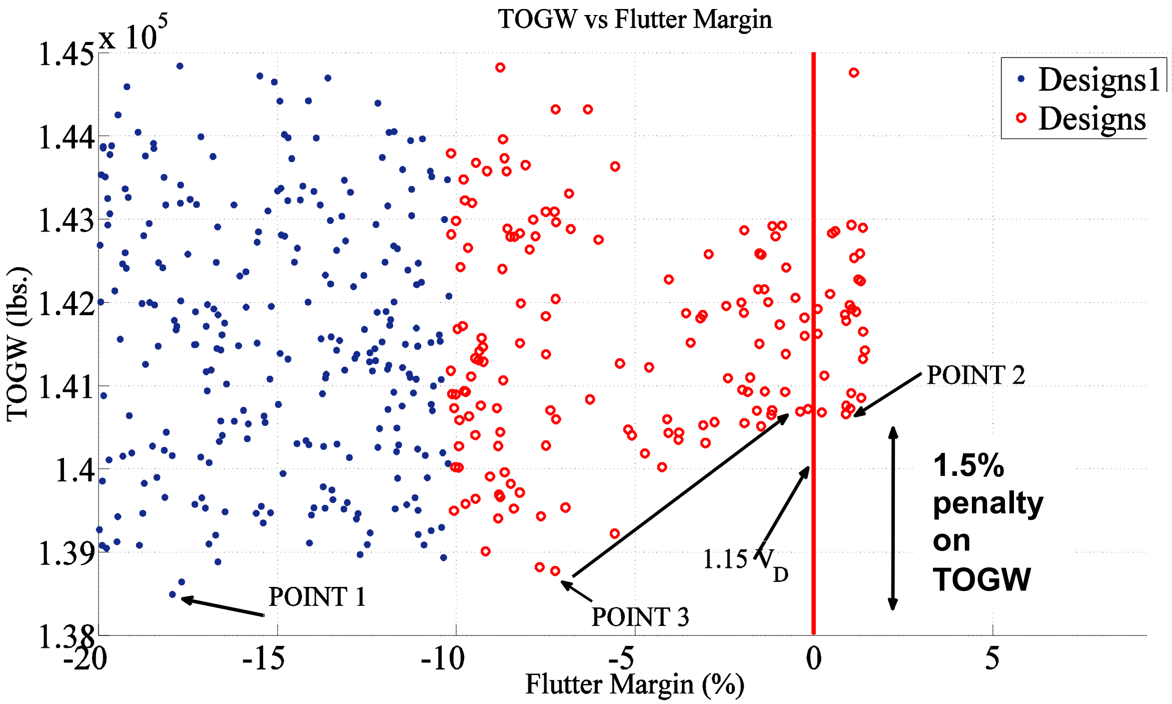
Aggressive Laminar
TBW
Min. Fuel

Previous TBW MDO Study Conclusions

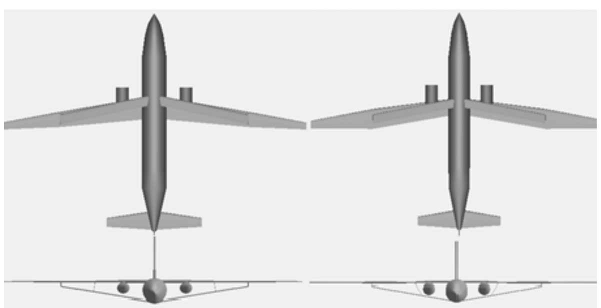
- TBW can improve performance
  - Lower structural weight for the same/higher span
  - Lower fuel weight
  - Lower t/c
  - Increased stiffness – lower deflection
- Min. TOGW design exhibits good structural/fuel weight compromise
- VT showed (results obtained without applying a flutter constraint)
  - up to 8% reduction in TOGW and 18% reduction in fuel burn for long-range mission with TBW/SBW over conventional cantilever
  - up to 3.6% reduction in TOGW and 9% reduction in fuel burn for medium-range mission for TBW/SBW over conventional cantilever

Effect of flutter constraint in MDO studies of TBW

Min TOGW Flutter Results – Medium-range

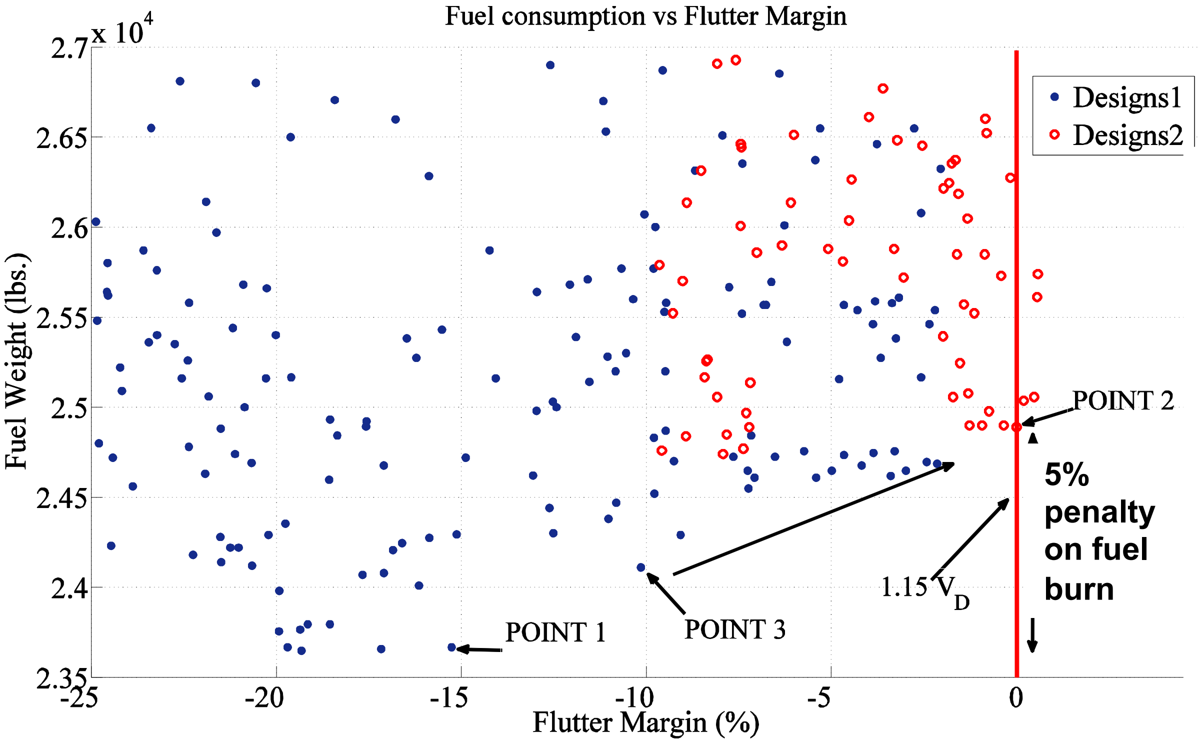


	POINT 1	POINT 2
TOGW (lbs.)	**138,400**	**140,600**
Fuel wt. (lbs.)	26,600	26,500
Struct wt. (lbs.)	24,500	27,500
Wing/strut semi-span (ft.)	75.8/ 46.7	78.8/ 50.9
Root Chord (ft.)	13.0	9.6
Strut-wing junc. chord (ft.)	8.8	12.0
Tip Chord (ft.)	4.0	5.8
Strut chord (ft.)	5.9	5.3
Jury chord (ft.)	2.4	3.1
Root t/c	0.111	0.051
Strut-wing junc. t/c	0.100	0.118
Tip t/c	0.107	0.050
Strut t/c	0.100	0.090
Jury t/c	0.090	0.095

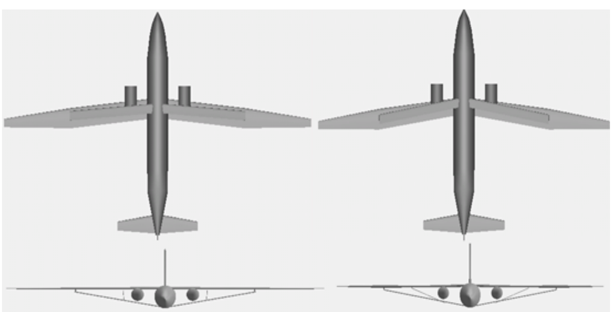


Flutter	POINT 1	POINT 2
Margin (%)	-17.60	1.30
Speed (KEAS)	367.2	427.6
Freq. (Hz.)	4.25	5.76

Min Fuel Flutter Results – Medium-range



	POINT 1	POINT 2
Fuel wt. (lbs.)	**23,700**	**24,900**
TOGW (lbs.)	141,000	142,500
Struct wt. (lbs.)	30,400	29,800
Wing/strut semi-span (ft.)	97.4/ 49.6	85.6/ 48.6
Root Chord (ft.)	14.4	14.6
Strut-wing junc. chord (ft.)	8.9	8.2
Tip Chord (ft.)	3.4	4.1
Strut chord (ft.)	3.6	4.0
Jury chord (ft.)	3.0	3.2
Root t/c	0.107	0.111
Strut-wing junc. t/c	0.136	0.122
Tip t/c	0.063	0.092
Strut t/c	0.083	0.115
Jury t/c	0.098	0.083



Flutter	POINT 1	POINT 2
Margin (%)	-15.30	0.01
Speed (KEAS)	372.6	417.2
Freq. (Hz.)	3.25	4.26

Aeroelastic benefits of Novel Control Effector to TBW via MDO study

Background

Motivation

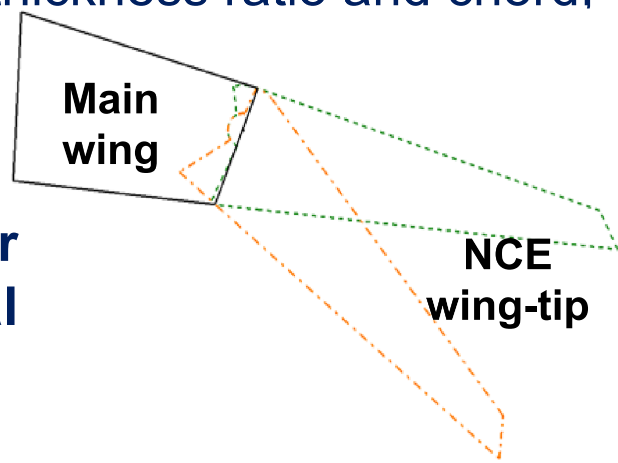
- Minimizing fuel burn (major objective - NASA N+3 Fixed Wing) results in flexible aircraft with large-aspect ratio (like truss-braced wing)
- Flexible truss braced wing (TBW) aircraft prone to control reversal and aeroelastic instabilities especially as span increases

Conventional solution to aeroelastic problems

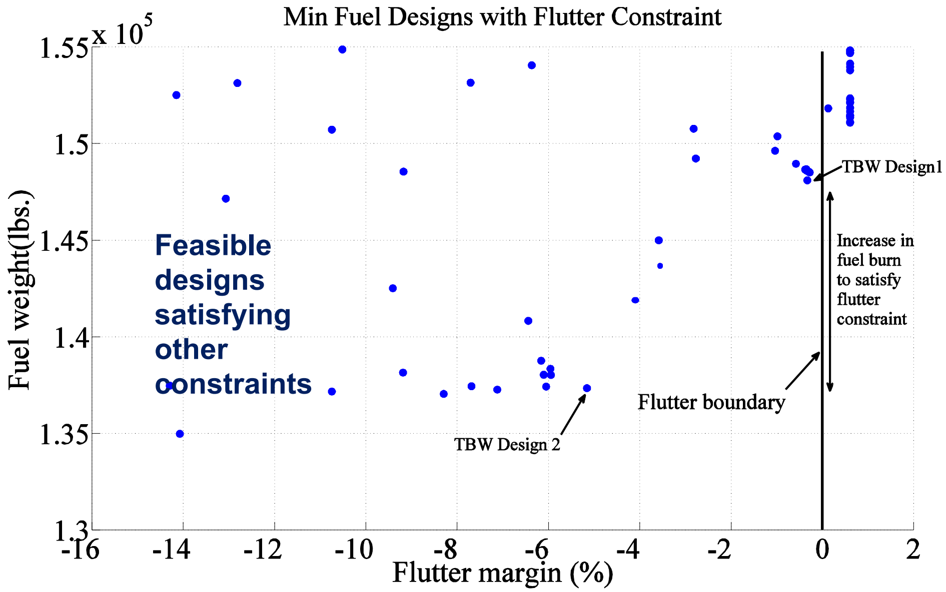
- increase in wing weight, additional control surfaces
- reduction in aerodynamic efficiency due to larger thickness ratio and chord, limited span

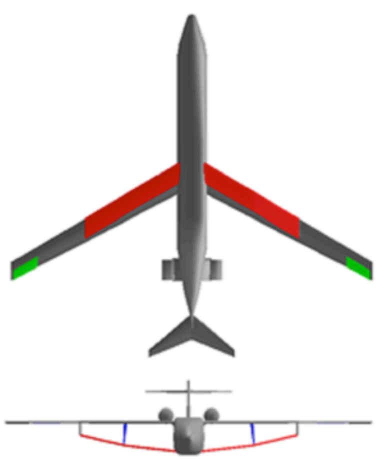
Alternative solution

- Aim – **retain sufficient aileron effectiveness for roll control either conventionally or in reversal**
- Develop a novel control effector (NCE) – a wing tip with variable sweep
- Use VT MDO to search a large number of probable good fits for the NCE

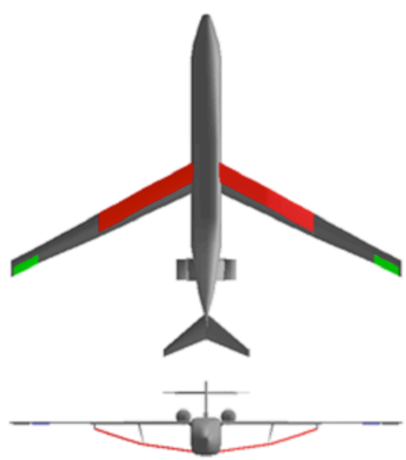


MDO results – TBW (Fuel weight v flutter margin)





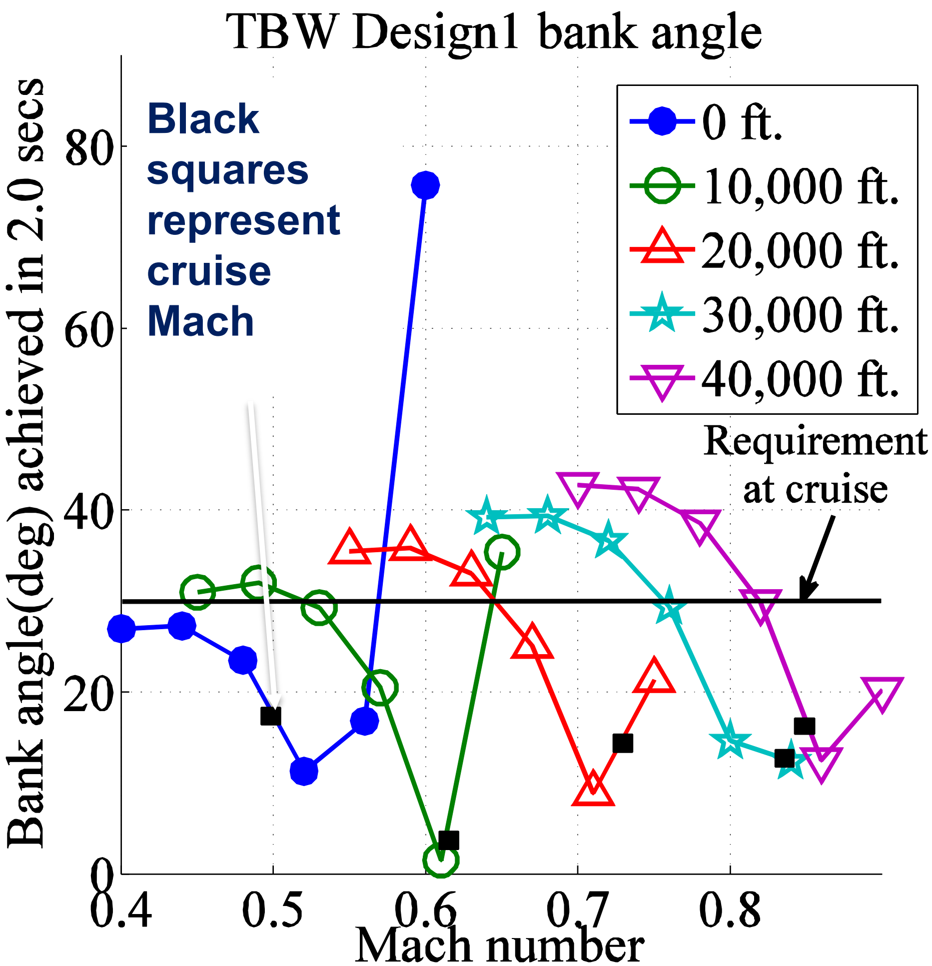
TBW Design 1

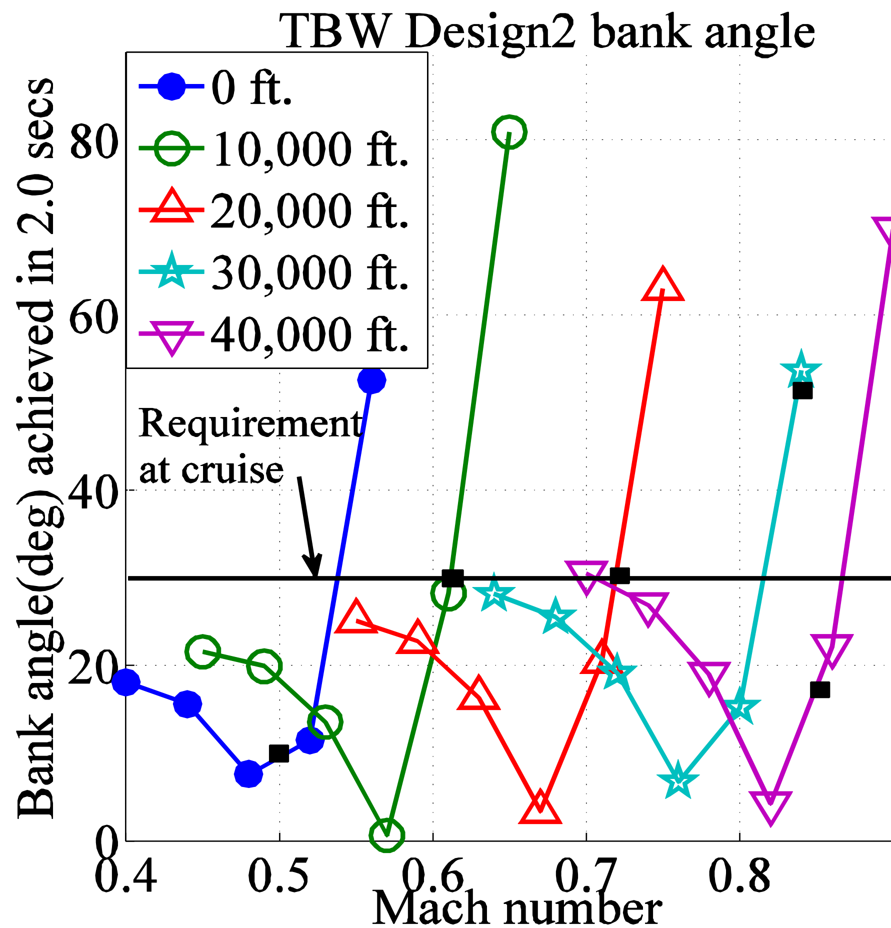


TBW Design 2

Design Parameters	TBW Design 1	TBW Design 2
Fuel wt. (lbs.)	149,000	138,000
TOGW (lbs.)	479,000	476,700
Wing/strut semi span (ft.)	121.35/ 71.68	130.64/ 71.39
Root chord (ft.)	20.69	20.89
Tip chord (ft.)	15.35	11.10
Strut chord (ft.)	11.98	13.10
Root chord (ft.)	3.00	3.03
Root t/c	0.113	0.114
Tip t/c	0.091	0.085
Strut t/c	0.100	0.110
Root t/c	0.080	0.078
Flutter margin	-0.33	-5.53

Roll motion of TBW designs





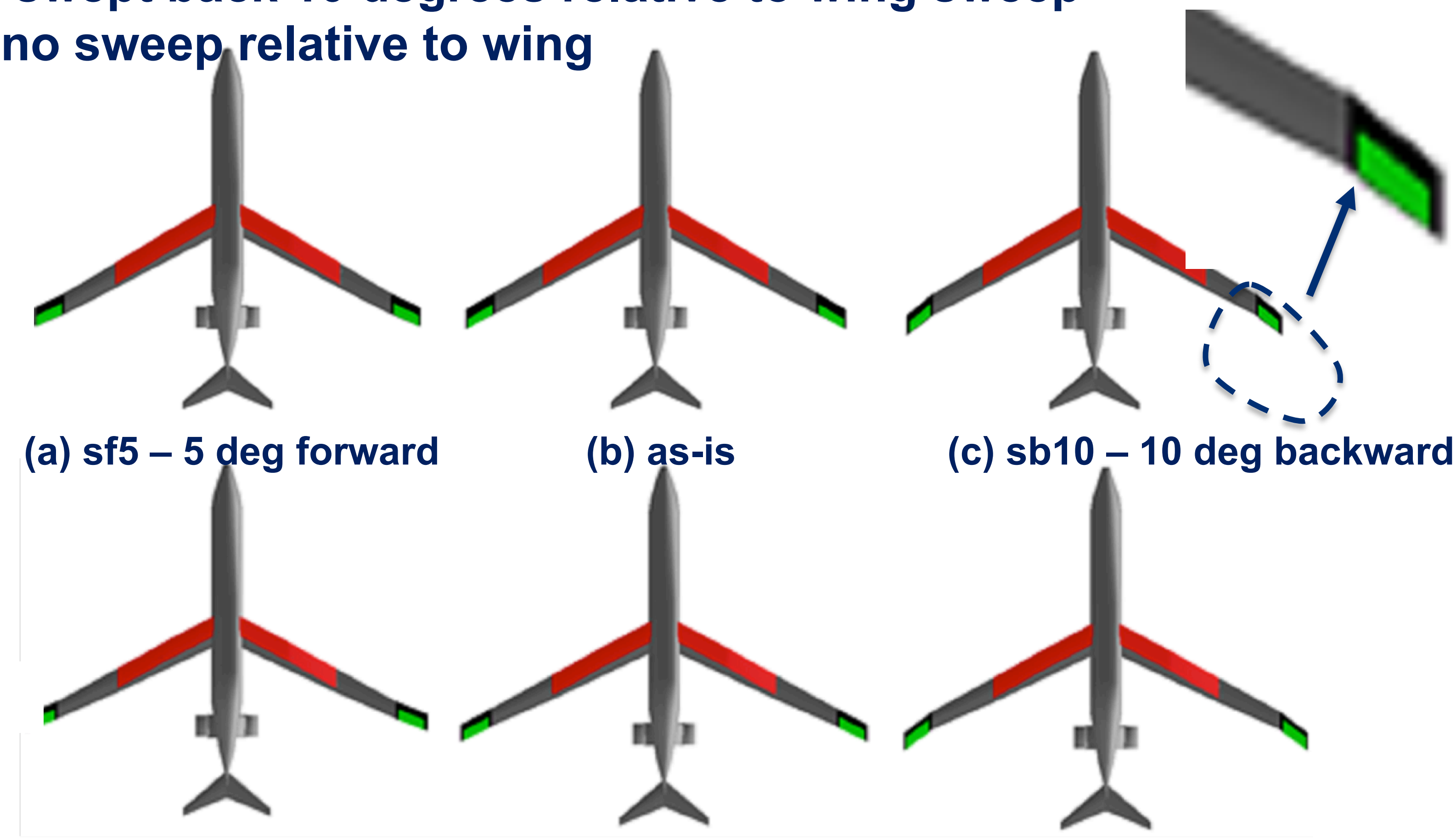
- **TBW not sufficiently flexible to achieve required bank angle**
- **NCE wing-tip required**

TBW designs with NCE wing-tip

- **Various forward and backward sweep angles NCE wing-tip (~15% of span) applied to the TBW**
- **Swept wing-tip labels**
  - **sf5: swept forward 5 degrees relative to wing sweep**
  - **sb10 : swept back 10 degrees relative to wing sweep**
  - **as-is: no sweep relative to wing**

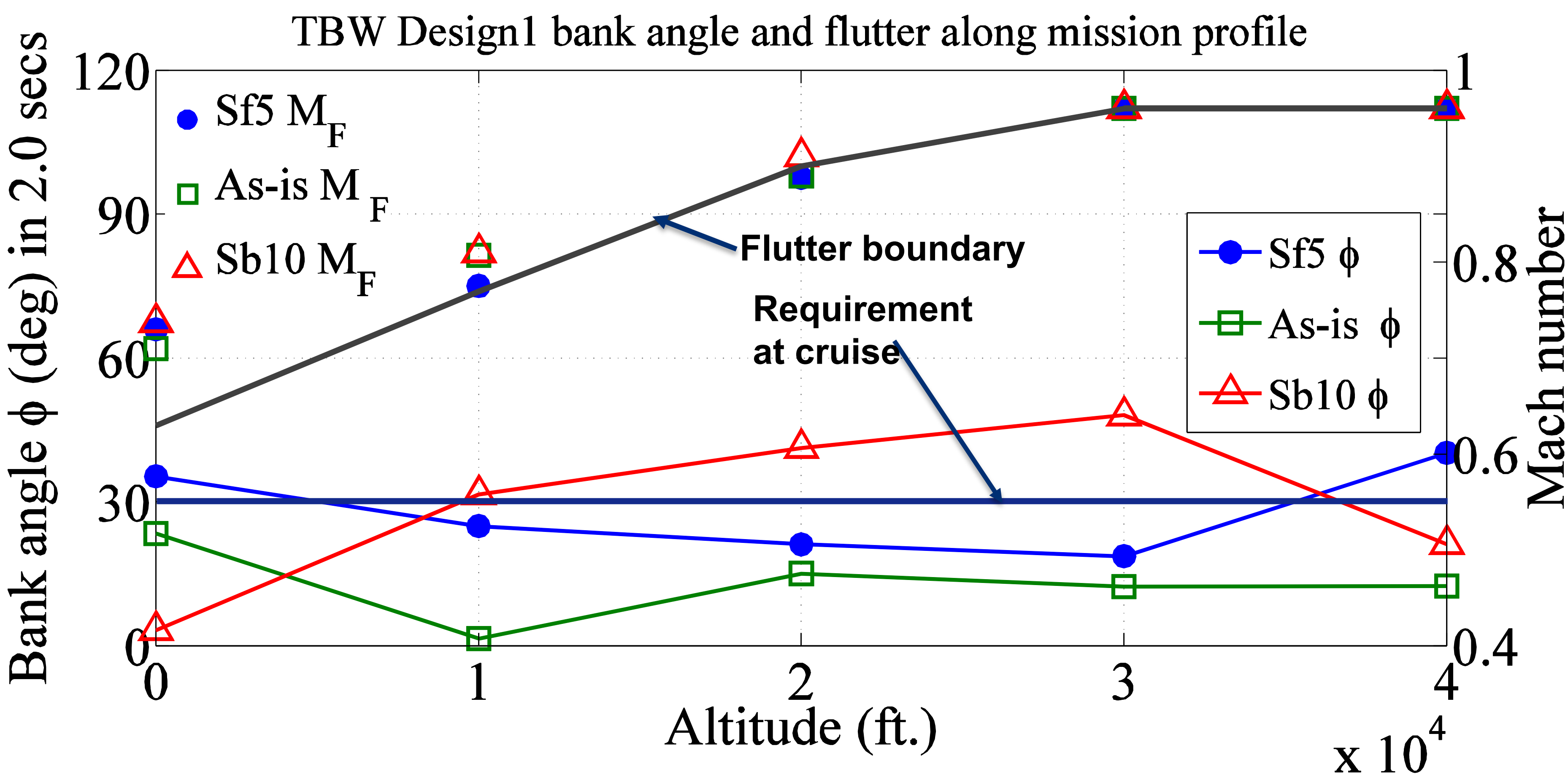
TBW Design 1:

TBW Design 2:



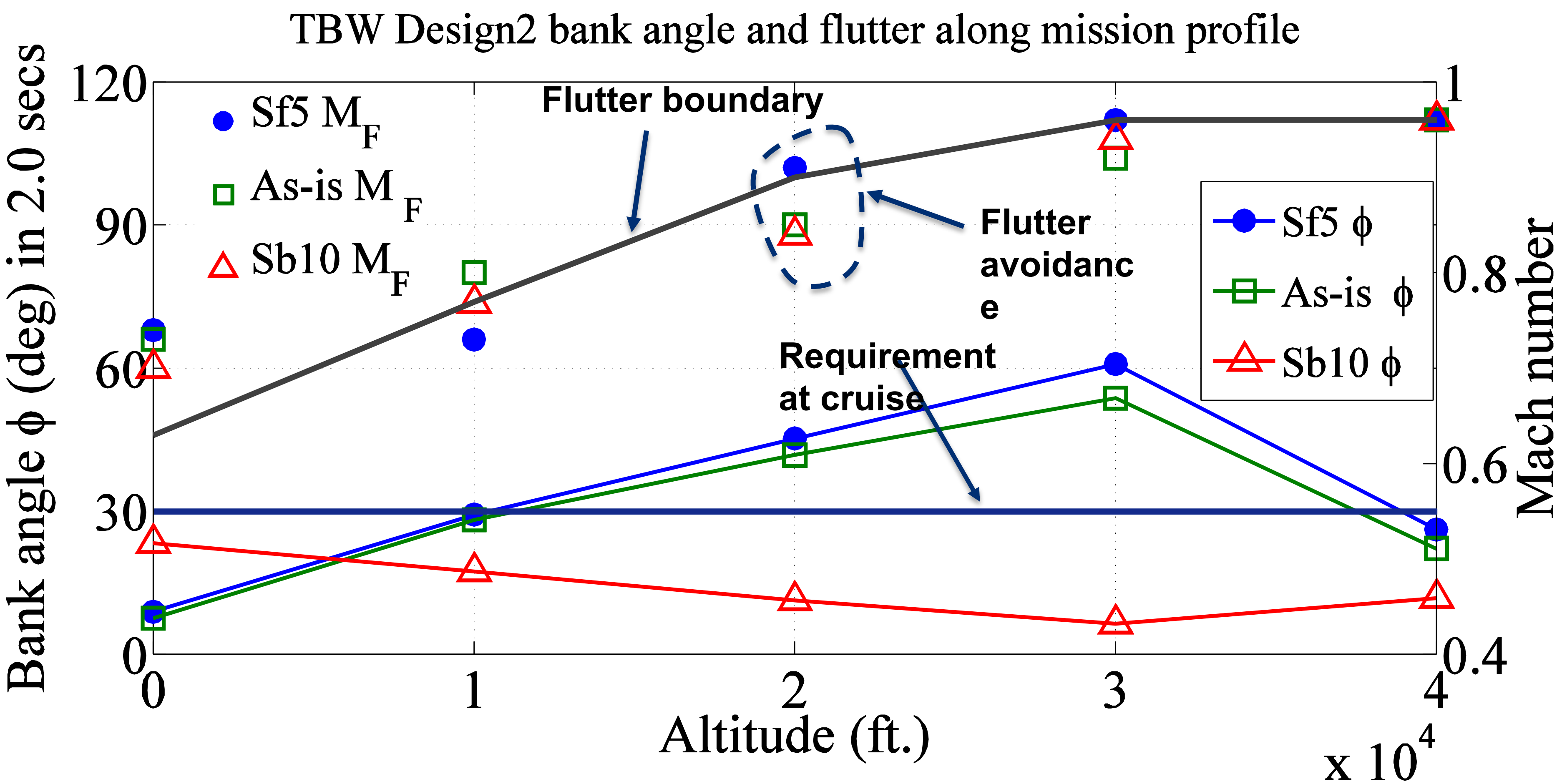
(a) sf5 – 5 deg forward **(b) as-is** **(c) sb10 – 10 deg backward**

Flutter & bank angles for TBW design 1 with NCE



NCE tip helps TBW design 1 to meet the required bank angles and also helps to meet the required flutter margin

Flutter and bank angles for TBW design 2 with NCE



NCE tip helps TBW design 2 to meet the required bank angles and also helps to meet the required flutter margin

Comparison of cantilever with NCE aided TBW

Design parameters	Cantilever	TBW Design 1 no NCE	TBW Design 1 with NCE	TBW Design 2 no NCE	TBW Design 2 with NCE
Fuel weight (lbs.)	157,000	149,000 (-5.1%)	149,000 (-5.1%)	138,000 (-12.1%)	138,000 (-12.1%)
TOGW (lbs.)	482,000	479,000	479,000	476,700	476,700
Flutter margin (%)	Does not flutter	-0.33	Constraint satisfied	-5.53	Constraint satisfied
Critical bank angle at cruise (degs.)	Constraint satisfied	12 (<< 30)	Constraint satisfied	18(<30)	28.6(~30)

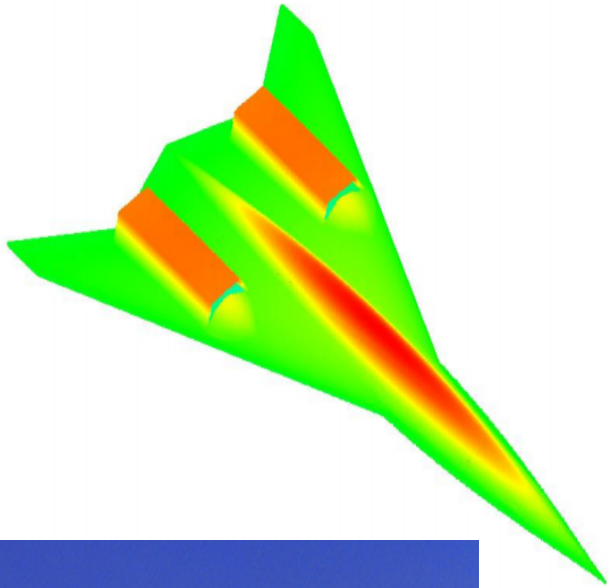
Conclusion

- **NCE wing-tip helps TBW design 1 to meet required roll control capabilities and reduce fuel burn by 5.1%**
- **NCE wing-tip helps TBW design 2 to almost meet the roll control requirement and aid in flutter avoidance – reduces fuel burn 12.1%**

Tailless supersonic aircraft MDO research

Motivation

- Bring physics based analyses forward into conceptual design stage
  - ❑ Traditionally rely on empirically bas
  - ❑ Advantages of physics-based meth
    - Identifies problems/issues that could sl
    - Produces overall better designs
      - Multi-fidelity analyses can be used to c regions of design space with minimal c
    - Reduces late stage costs



Solution

➢ **Aircraft MDO Framework (N^2)**

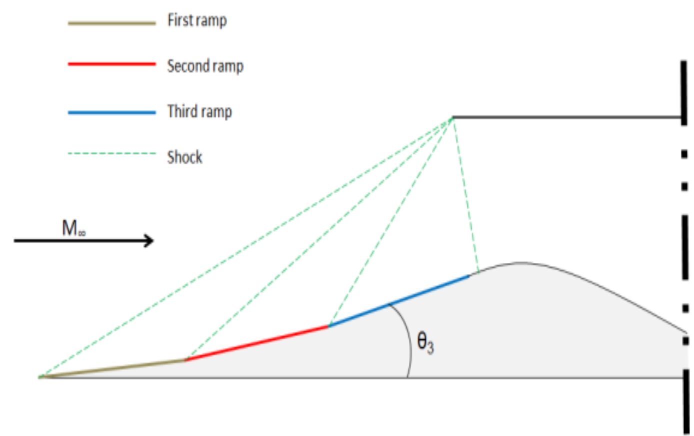
- Developed a multi-disciplinary, multi-fidelity design, analysis, and optimization framework for aircraft conceptual design
- Each module (discipline) can be either an analysis or an optimization within itself

Medium-Fidelity Tailless Supersonic N^2 Diagram

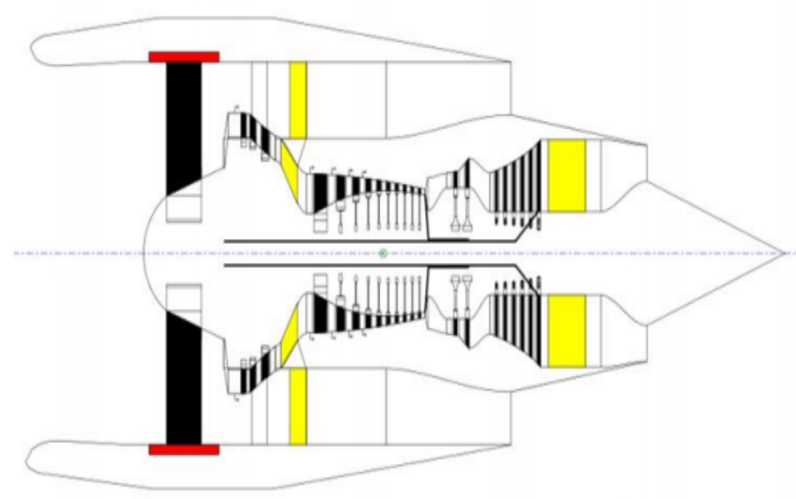
Propulsion	Flow behind inlet shocks	Flow-through panels' data	Temp., Press., Alt., M, Dimen.	Engine weight	Engine weight	Engine data in flight envelope	Exhaust speed & temp., Noz. Dim.		Thrust, Altitude, Mach #, BPR, etc.
Cowl and Inlet	**Geometry**	Configuration, Mach #, Alt.	Cowl, Aft deck	Configuration	Tank and engine locations	Wing area	Noise shielding factor	Configuration, Avail. fuel vol.	Configuration
		Aerodynamics	Skin temp., Loading			Aero. data in flight envelope			
			EEWS	EEWS weight	Structural weight - EEWS				
				FLOPS Structures	Structural weight - other				
					FLOPS Weights	Aircraft weight in flight envel.			TOGW
						FLOPS Mission Performance	Detailed take-off parameters	Req. fuel volume	Feasibility
							FLOPS Noise	Noise output	
								Constraints	Feasibility
Thrust, Altitude, Mach #, BPR, etc.	Configuration								**Optimization**

Propulsion Module

- ➤ Low-fidelity
  - ❑ Flight Optimization System (FLOPS)
    - Based on Navy NASA Engine Program
    - Calculates engine analysis: thrust, fuel flow, etc. at given atmospheric flight conditions
    - Limitations
      - ➤ Thrust related to type of aircraft
      - ➤ Weight estimate
      - ➤ No dimensions

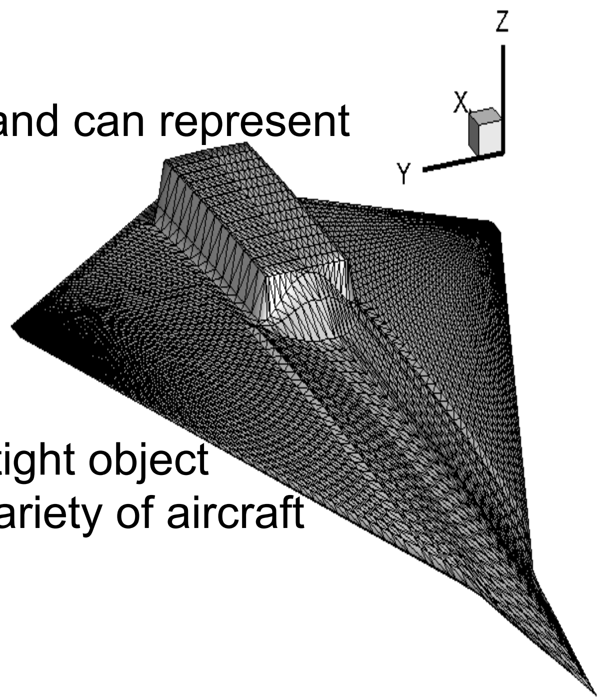


- ➤ Medium/High Fidelity
  - ❑ Numerical Propulsion System Simulations (NPSS) & WATE++
    - Performs engine analysis
    - Produces better (more accurate) estimate of weight
    - Calculates dimensions



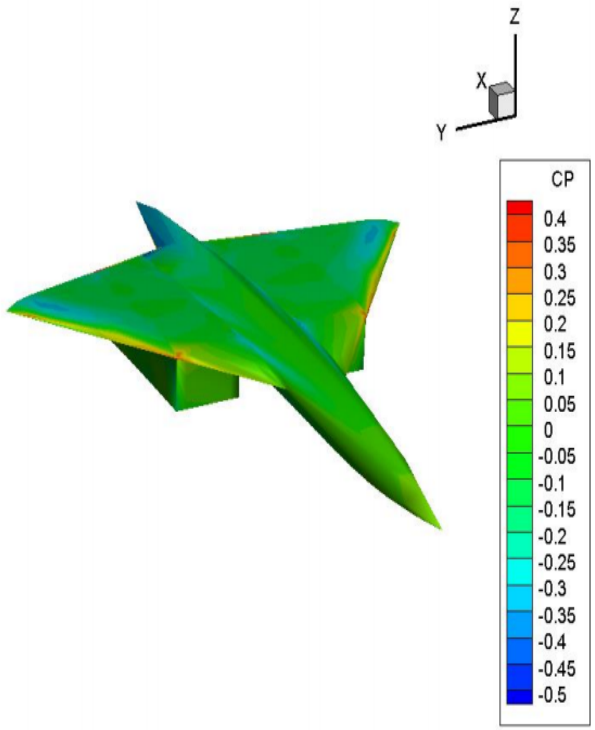
Geometry Module

- Virginia Tech Class-Shape Transformation (VT-CST)
  - Parametric mathematical model to describe the outer mold-line shape of
    an aircraft
    - Based on Kulfan CST developed at Boeing
    - Equations (Bernstein polynomials) are analytic and can represent a variety of common shapes
      - Airfoil
      - Wing
      - Cowl
      - Ramp
      - Fuselage
    - Shapes can be combined to form overall water-tight object
    - Geometry model easily extensible to handle a variety of aircraft configurations
      - Multiple wings
      - Multiple fuselages
      - Multiple engines
    - Code written in object-oriented C++ and is platform independent



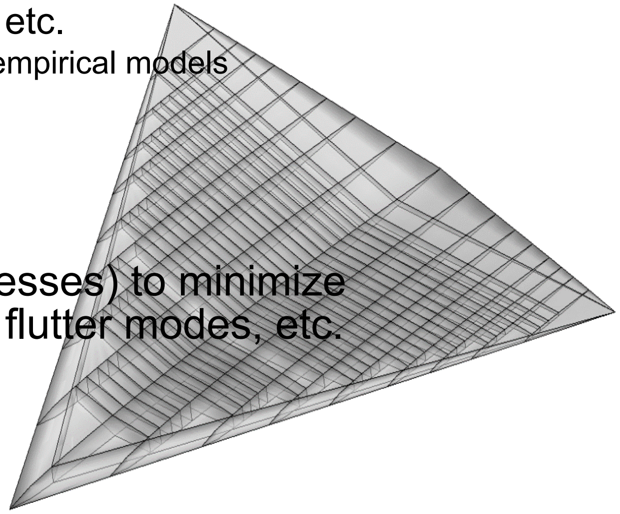
Aerodynamics Module

- Low-fidelity
  - WingDes
    - 2D panel method - can only represent clean wing
    - Lift and induced drag coefficients
  - Friction
    - Viscous and pressure drag coefficients
  - AWAVE
    - Wave drag coefficient
- Medium-fidelity
  - Zonair
    - 3D panel method for entire aircraft geometry to genera aerodynamic information at both subsonic and supers speeds
    - Can represent control surfaces and calculate stability
- High-fidelity
  - Computational Fluid Dynamics
    - This capability is currently in development
  - Wind Tunnel Testing
    - Rapid prototyping (3D-printing) can be used to quickly generate models that are used for wind tunnel tests
    - This capability is currently in development

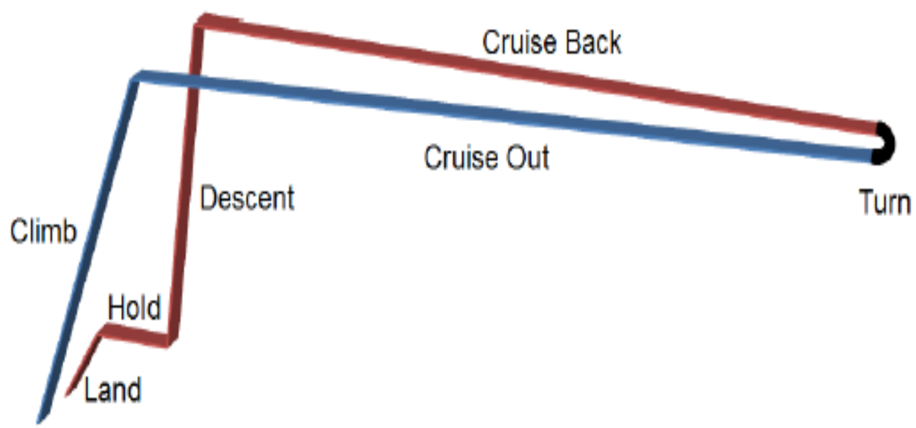


Weight Estimate Module

- Low-fidelity: Empirical estimate
  - FLOPS Weight Generator
    - An empirical weight estimate of structural and nonstructural mass based on ultimate and maneuvering load factor
      - Based on aircraft: Convair B-58A, North American B-70, North American A-5, General Dynamics F-111A/B, Republic F-105D, McDonnel Douglas F-4B/E
- Medium-fidelity: Structural Finite Element Analysis (under development)
  - Automatic Generation of a structural model for finite element analysis
    - Geometry module utilized to develop mesh based on input parameters
      - Number and locations of bulkheads, spars, ribs
      - Material properties
      - Non-structural weight information, e.g. fuel, payload, etc.
        - This information currently must be generated through empirical models
  - Finite Element Analysis in NASTRAN
    - Analyses: static aeroelasticity, flutter, buckling
  - Structural Optimization
    - Optimize structural configuration (layout and thicknesses) to minimize weight subject to constraints on stresses, buckling, flutter modes, etc.

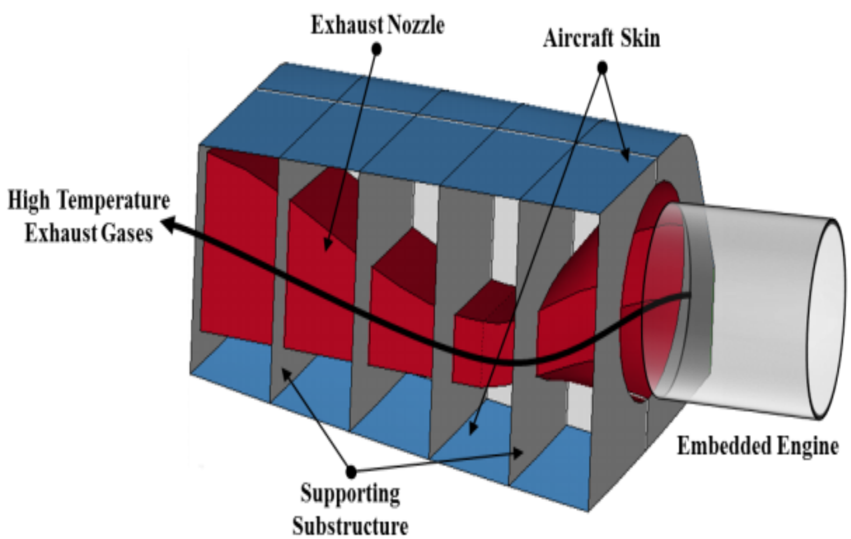


- FLOPS
  - Mission is specified:
    - Take off and landing field lengths, speed, etc.
    - Each leg of flight in terms of distance and altitude
  - Code determines fuel burned (required within the aircraft) based on:
    - Weight information from Weight Estimate Module
    - Volume of fuel tanks from Geometry Module
    - Aerodynamic information (lift and drag coefficients) from Aerodynamics Module
    - Power available and fuel burn rates from Propulsion Module



Other Analysis Modules

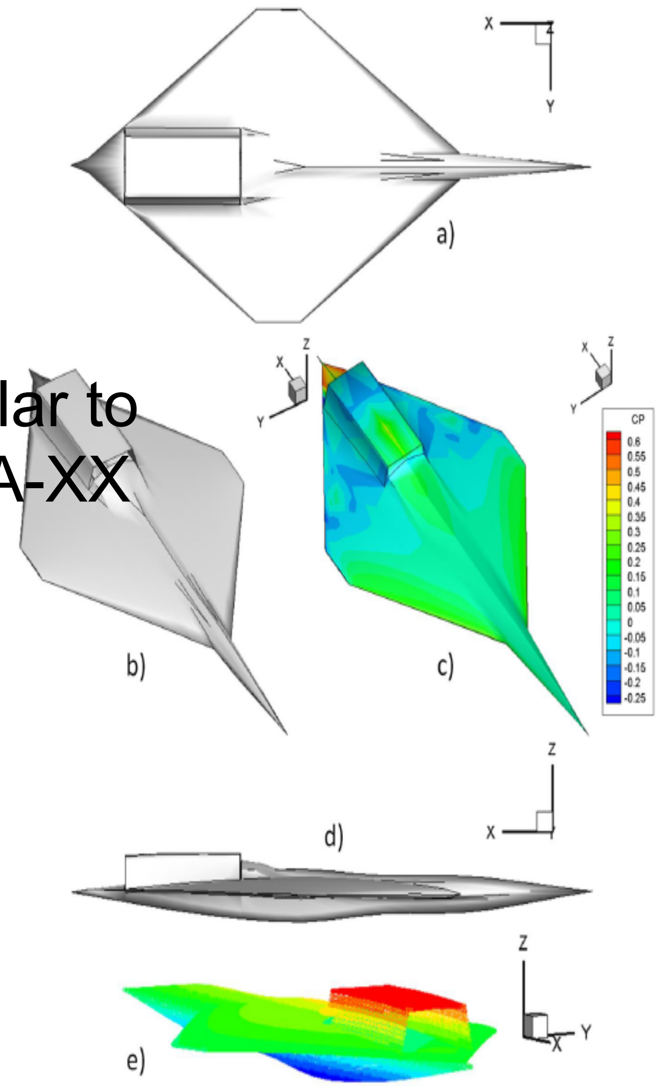
- Embedded Engine Exhaust-washed Structures (EEWS)
  - Identified early as a critical analysis – large impact on later design stages
  - Topology optimization of structures subject to mechanical and thermal loading



- Noise
  - Noise calculations performed by FLOPS mission analysis

MDO enabled designs – Medium Fidelity Framework

- Overall optimization
  - Two successive genetic algorithms
    - Genetic algorithms: NSGA-II
- Result
  - Trapezoidal aircraft configuration similar to Northrop YF-23 or Boeing concept F/A-XX



Future Work

- Currently under development
  - Stability Analysis
    - Rigid stability analysis developed, but not integrated into framework at present
    - Flexible stability analysis under development
  - Physics based weight estimate
    - Structural MDO – finite element analysis and aeroelasticity
  - High-fidelity aerodynamics
    - CFD
    - Rapid Prototyping and Wind Tunnel Testing
- Repeat optimization with new modules included

Benefits/ Drawbacks of ModelCenter

- **Benefits - Excellent multidisciplinary environment**
  - Readily available plug-ins - Matlab, ANSYS, NASTRAN, ABAQUS
  - Flexible plug-in (wrapper) – JAVA or Python scripts
    - User can develop in-house executables and use them
  - Links – Connects analysis to nodes each other or to optimization nodes
  - Several legacy optimizers available
  - Popular optimizers available with purchased license
  - Prompt customer service (proximity of Phoenix@VT CRC)
- **Needed Improvements– A LINUX version, and robust parallel processing framework**
- ModelCenter is only Windows – Linux based HPC nodes can be connected but via complicated route
  - Improved memory management for legacy optimizers
  - More documentation, currently has only simple examples - far from real life complicated examples which require parallel processing