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Application of High-Fidelity Computational Fluid Dynamics to Design Optimization for Missile Static Stability

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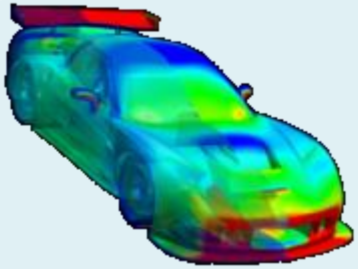
Corporate Summary

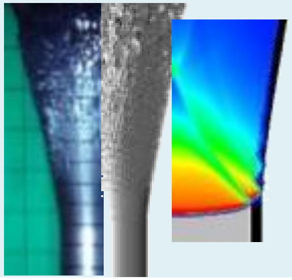


COMPUTATIONAL FLUID DYNAMICS

- Vehicle Aerodynamics
- Propulsion System Performance
- Blast Wave Dynamics
- Mixture Analysis
- Finite Rate Chemistry
- Rarefied Gas Dynamics

APPLIED TOOL DEVELOPMENT

- Real-world Engineering Applications
- Tool Customization
- Internal Development + Tech. Transfer Program
- Scalable, Efficient, Physics Modeling, Pre, Post
- Raven, Velodyne, HAVOC, CTH, VGI, GAVEL



SHOCK PHYSICS

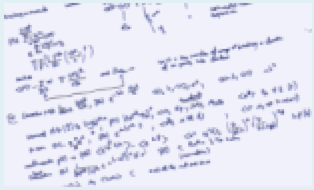
- Lethality & Weapons Effectiveness
- Hypervelocity Penetration Analysis
- Detonation Studies
- Material Characterization
- Lethal Volume Studies
- Blast Loading on Structures

EXPERIMENTAL TEST SUPPORT

- Test Design & Analysis (pre/post test)
- Instrumentation Design / Calibration
- Test Article Fabrication
- Integrated Approach → More Efficient
  - Reduced Testing
  - Increased Understanding (Why vs. What)

STRUCTURAL MECHANICS

- Late Time Effects
- High Strain Rate Mechanics
- Structural Design
- Penetration
- Weapons Lethality
- Intercept Debris



THEORETICAL RESEARCH

- 6.1 Fundamental Sciences (SBIR/direct)
- Material Characterization
- EOS Development
- Innovative Computational Techniques
- Late-time Structural/Thermal Response
- Numerical Database Development

DESIGN

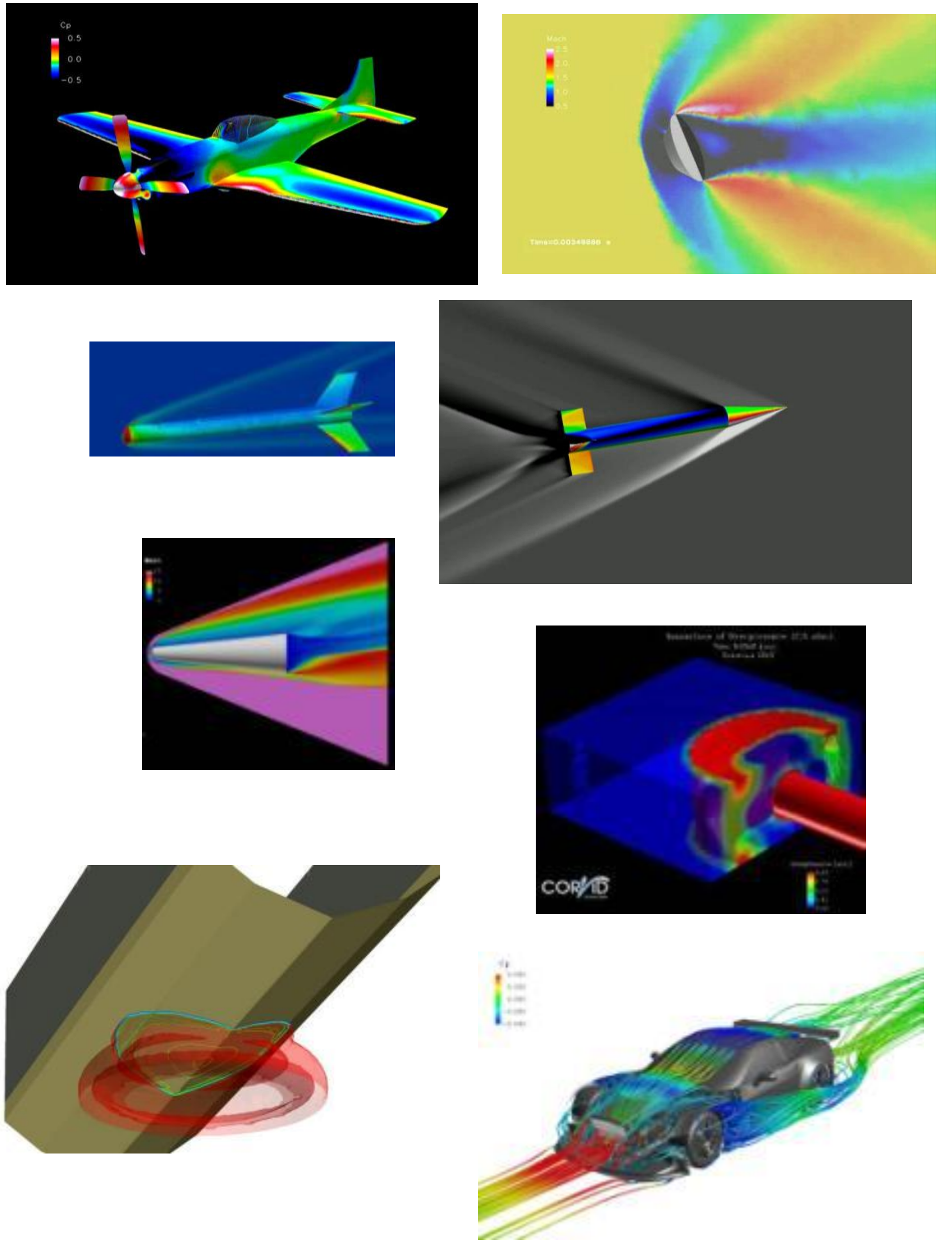
- Clean-Sheet Styling
- Class A Surfacing
- Scan Data
- Point Cloud Interpretation
- Reverse Engineering

COMPUTATIONAL RESOURCE

- In-House
- 5000+ CPU (*6000+ in 2012*)
- 200 TB Data Storage
- High Speed Interconnect
  - Gigabit + Infiniband

RAVEN CFD

- In-House-Developed Navier-Stokes flow solver
  - Tailored to customer requirements
- 3D arbitrary unstructured grid
- Robust, time-accurate implicit formulation
- Scalable to 1000s of processors
- Advanced capabilities
  - Dynamic/transient motions
  - Accurate over wide rage of Mach numbers
  - Internal shape optimization capabilities
- Auxiliary tools
  - Pre/post processing tools
  - Increased efficiency and throughput
  - Large scale databasing tools
- Continuing development



Corvid Missile Program Support

Aerodynamic Metrics

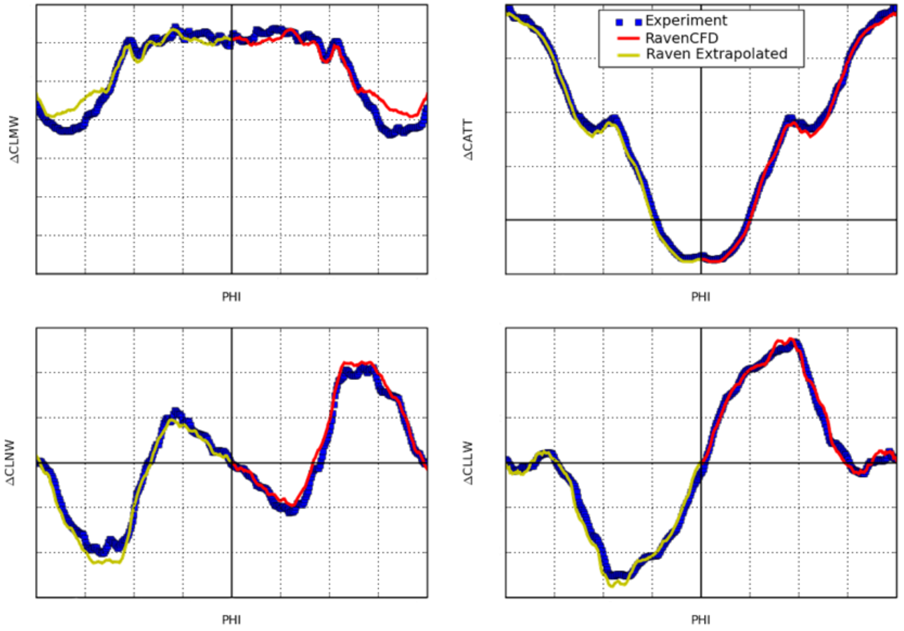
- Forces and moments
- Center of pressure
- Means and standard deviations
- Aerodynamic loading
- Static stability performance analyses

Why vs. What

- Component vs. global loads
- Data probing
- *Cause versus effect*

Beyond the Tunnel

- Full-scale geometry
- Flight conditions
- Dynamic capabilities
- Virtually limitless design changes



🟥 = largest deltas

Force & Moment Comparisons by Component

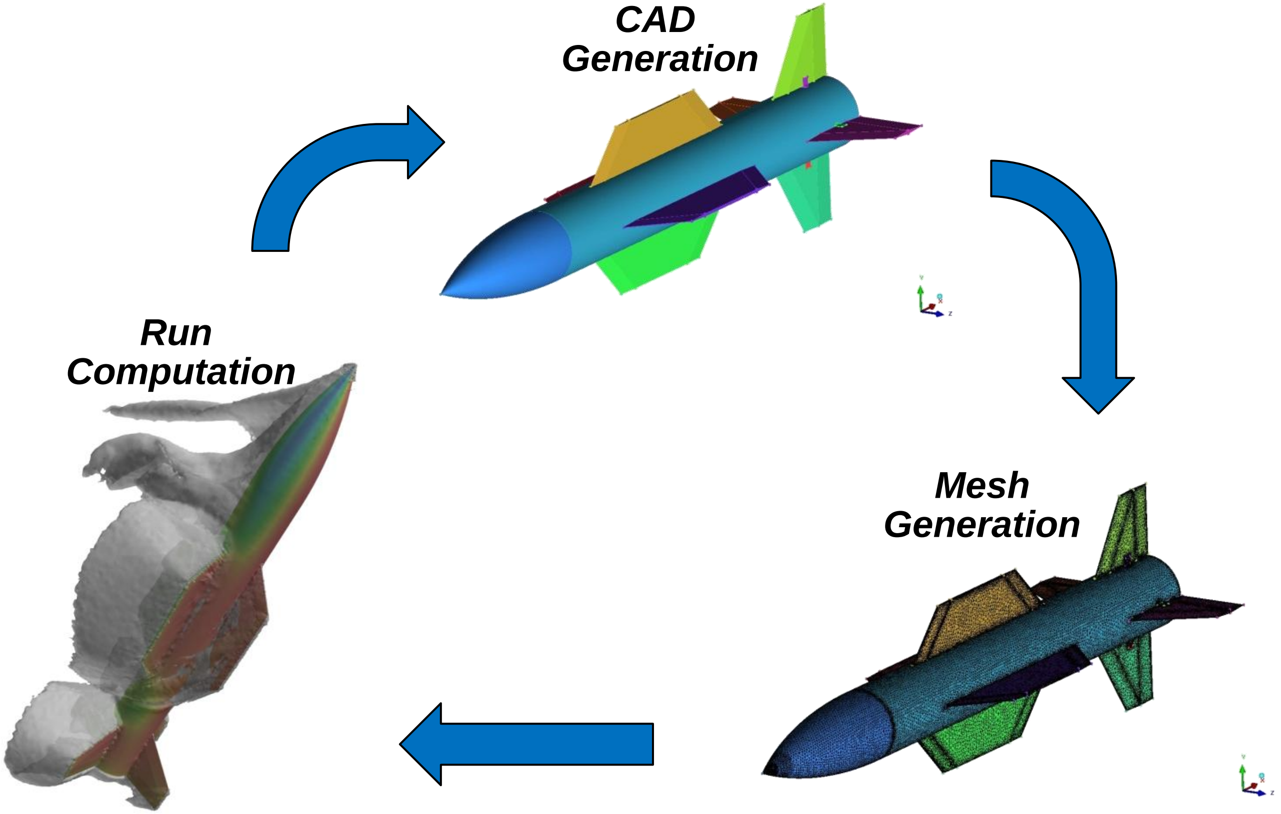
Component	Drag			Lift			Pitching Moment		
	P1FB	P2FB	Delta	P1FB	P2FB	Delta	P1FB	P2FB	Delta
WARHEAD"	9.319	9.790	*0.471*	15.478	16.035	*0.557*	-2406.109	-2502.229	*-96.120*
TAIL_FIN_4"	35.169	36.574	*1.406*	59.512	64.809	*5.297*	-583.352	-625.499	*-42.147*
TAIL_FIN_3"	-4.044	-4.803	*-0.759*	-10.623	-11.766	*-1.143*	161.239	169.580	*8.341*
STEERING_CONTROL_SHROUD_BASE"	15.268	13.567	*-1.701*	-7.441	-6.597	*0.844*	-1.959	-6.610	*-4.652*
STEERING_CONTROL_SHROUD"	11.393	11.620	*0.226*	5.922	7.150	*1.229*	-110.584	-116.330	*-5.746*
ROCKET_MOTOR"	73.847	73.203	*-0.644*	138.070	135.290	*-2.780*	-10631.020	-10437.434	*193.586*
GUIDANCE"	23.634	23.657	*0.023*	84.945	83.589	*-1.356*	-14617.030	-14362.778	*254.253*
FORWARD_SHOE_2"	1.126	1.085	*-0.040*	0.055	0.041	*-0.014*	-47.812	-44.960	*2.853*
FORWARD_SHOE_1"	3.221	3.120	*-0.101*	2.002	1.927	*-0.075*	-342.453	-330.671	*11.781*
DORSAL_FIN_4"	88.906	86.757	*-2.149*	180.743	175.529	*-5.214*	-16914.152	-16472.444	*441.707*
DORSAL_FIN_3"	51.028	50.298	*-0.730*	101.443	99.252	*-2.191*	-9546.066	-9304.164	*241.902*
AUTOPILOT_BATTERY"	11.814	11.661	*-0.153*	22.402	21.888	*-0.515*	-2929.690	-2868.675	*61.015*
AFT_SHOE_2"	0.460	0.443	*-0.016*	-0.369	-0.373	*-0.004*	7.476	7.652	*0.175*
AFT_SHOE_1"	1.117	1.138	*0.021*	0.441	0.440	*-0.001*	-27.325	-27.678	*-0.353*

Evolution of Aerodynamic Databasing

- Large cost and schedule requirements historically associated with high-fidelity N-S CFD aerodynamic databases (aeromaps)
  - Grid generation can be cumbersome
  - Days to weeks of run time
- Cost cutting often achieved by developing aeromaps using low-fidelity approaches (panel methods, Euler solvers, etc…)
  - Fast running capability
  - Geometric complexities can constrain these methods
  - Missing physics
  - Restrictive in Mach regimes
- Improvements in grid generation, CPU power, and numerical methods now make N-S CFD aeromaps realizable
- Corvid’s aeromap development experience
  - Subsonic aeromaps developed and married to low-fidelity supersonic map for booster and booster+fin configuration
  - Five month development of abbreviated aeromap for an advanced missile system
    - Seven configurations with steering increments
    - 800+ wind-tunnel type runs (Pitch and Roll sweeps for subsonic, transonic, and supersonic Mach numbers)
    - O(3,500,000) CFD data points

Typical NS-CFD Databasing Procedure

- Development of CAD for configuration of interest
- Develop computational mesh
- Perform computational analysis
- Repeat the procedure for each additional configuration
- *Costly process for large numbers of configurations*



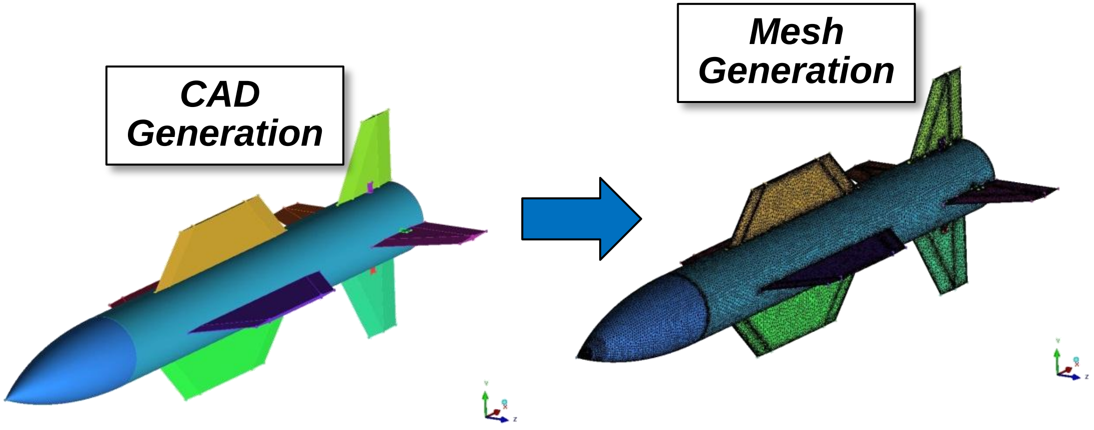
CAD Generation

Mesh Generation

Run Computation

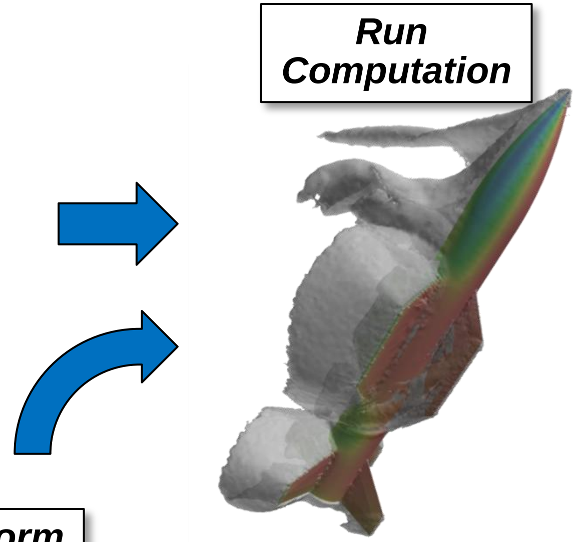
Corvid Databasing Procedure

- **Development of CAD for configuration of interest**
- **Develop computational mesh**
- **Perform computational analysis**
- **Deform grid and repeat calculations**

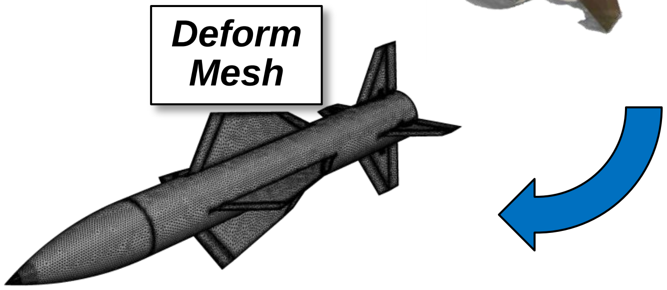


CAD Generation

Mesh Generation



Run Computation



Deform Mesh

- **Pros:**
  - **Simple and cost effective**
  - **Can be easily automated**
- **Cons:**
  - **Limitations on deformations**
  - **Requires some forward thinking during the grid gen process**

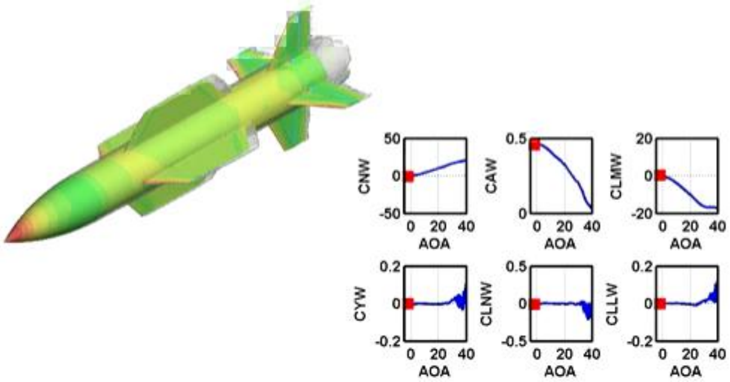
Rigid Body Motion

- Collection of static data points would result in sparse resolution through AOA space and would be very costly

- Utilize rigid body motion pitch and roll sweeps, similar to what would be performed in wind-tunnel tests

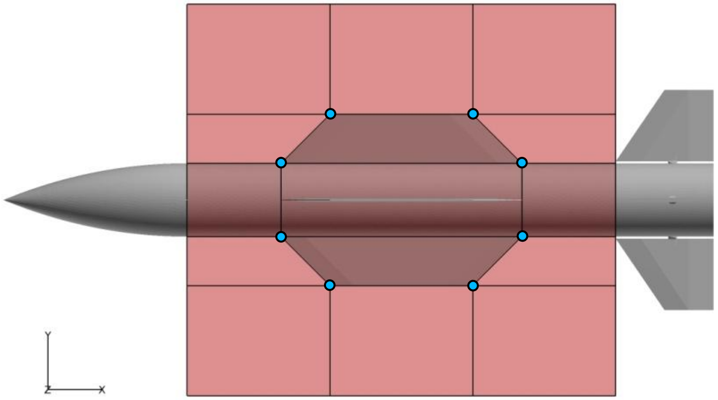
- Yields higher resolution in either roll or pitch space

- Time-accurate solutions cost more but faster than running several static cases

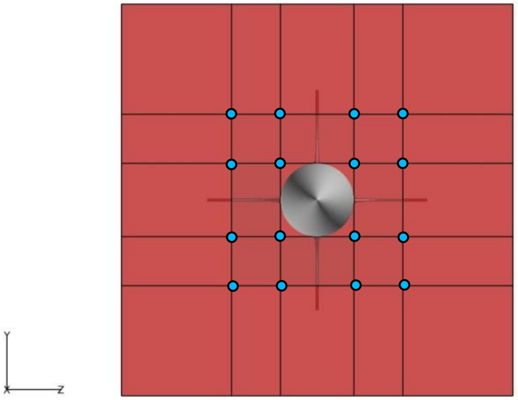


Embedded Shape Deformation

- Shape deformation capability embedded in RavenCFD utilized for dorsal transformations
- Deformations controlled by moving intersections of deformation volumes
- Deformations currently controlled by the user, but can be (and has been) easily coupled to an optimization routine and controlled within RavenCFD



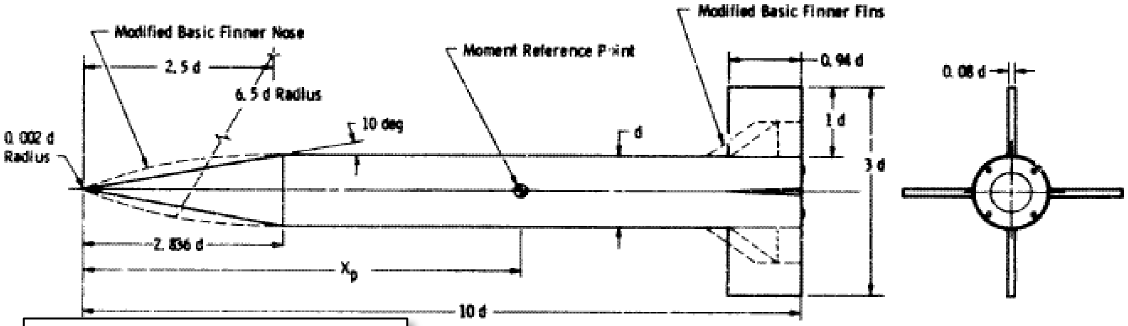
Side view of deformation volume.



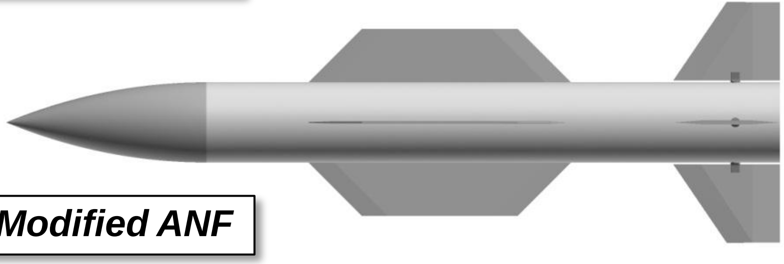
Front view of deformation volume.

Baseline Configuration

- Demonstration on “open source” geometry
- Adapted from the modified Army Navy Finner (modified ANF or basic finner) geometry described AEDC-TR-76-58 report
- Added dorsal fins, tail fin posts, and extended tail fin heights to be representative of typical missile geometries



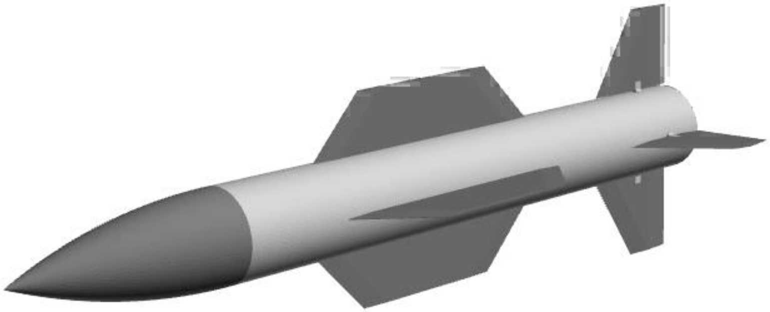
ANF – Basic Finner



Corvid Modified ANF

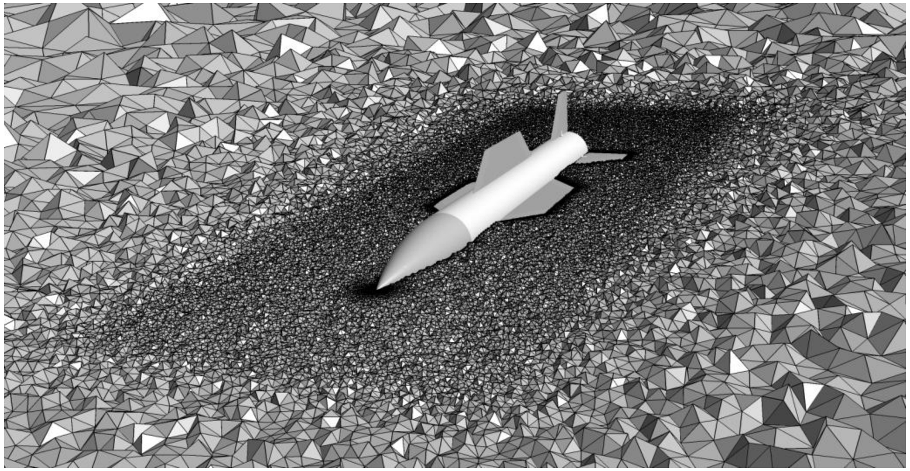
Design Space

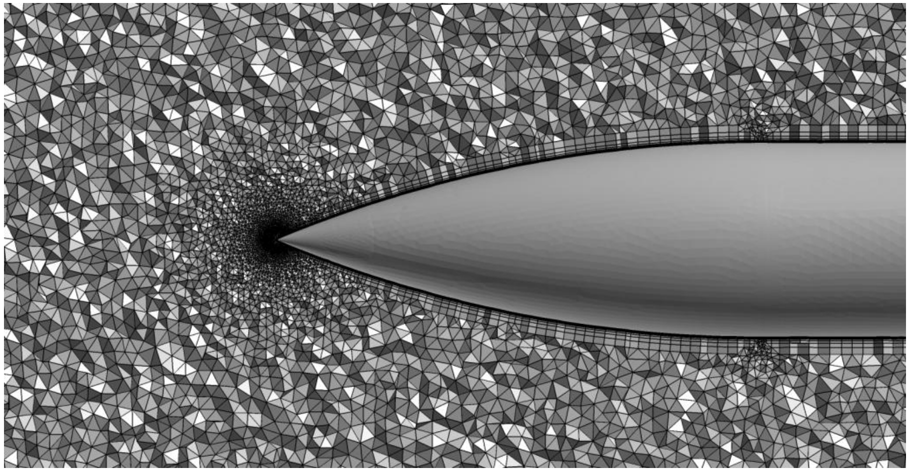
- ***Design Objective:*** **Design to egress performance while optimizing cruise G capability (i.e. maneuverability)**
- ***Design requirement:*** **All components except dorsals must remain unchanged**
- **This restricts configurations changes to the dorsals only and greatly simplifies the process**
- **Four basic design variables are considered include: dorsal location, span, chord length, and sweep**
- **In this exercise 25 configurations considered, total of 58 continuous 70° pitch sweeps (~160,000 CFD data points)**

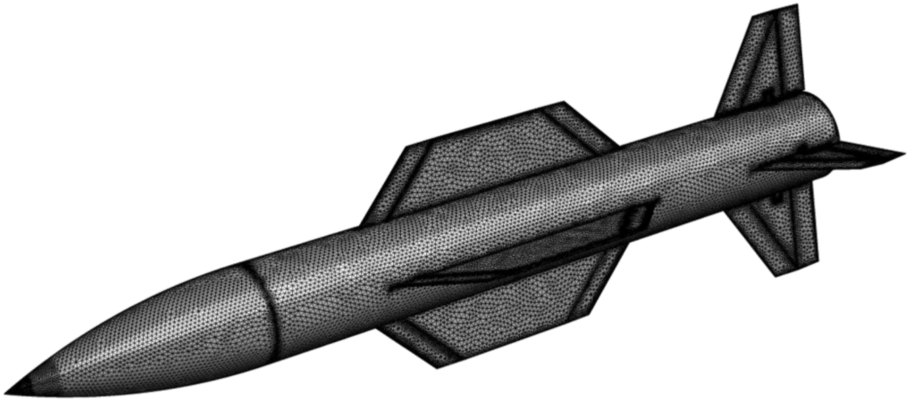


Computational Setup

- Geometry consistent with ANF tunnel models
- All calculations assume sea-level conditions
- Grid generation techniques consistent with Corvid production missile runs
- Computational grid consists of 18.7M cells
- Near wall boundary layer cells sized for Mach 0.30 condition





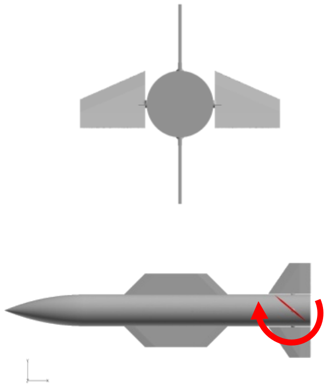


Fin Increment Maps

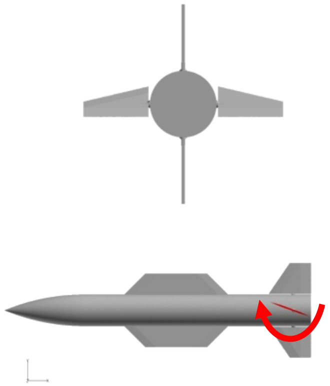
- **Fin effectiveness required for static stability assessment**
- **Deflections were accomplished using standard grid generation techniques (deflections too large for grid deformation)**
- **Pitch steering increments of i = +/- 20° and +/- 40° were calculated for this aeromap exercise**

$$\left[i = \frac{\delta_{f2} - \delta_{f4}}{2} \right]$$

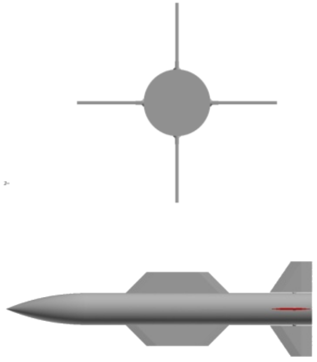
- **Baseline increment map utilized for all configurations**
- **Assume dorsal changes do not change fin increment map**
  - **Reasonable assumption for small dorsal changes at low-to-moderate AOA's**



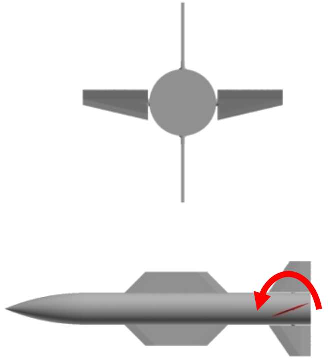
40° fin deflection



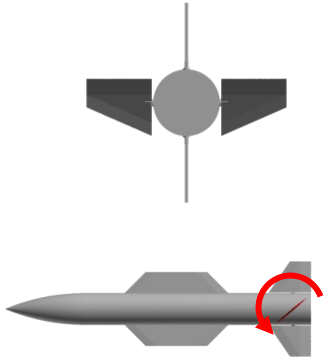
20° fin deflection



0° fin deflection



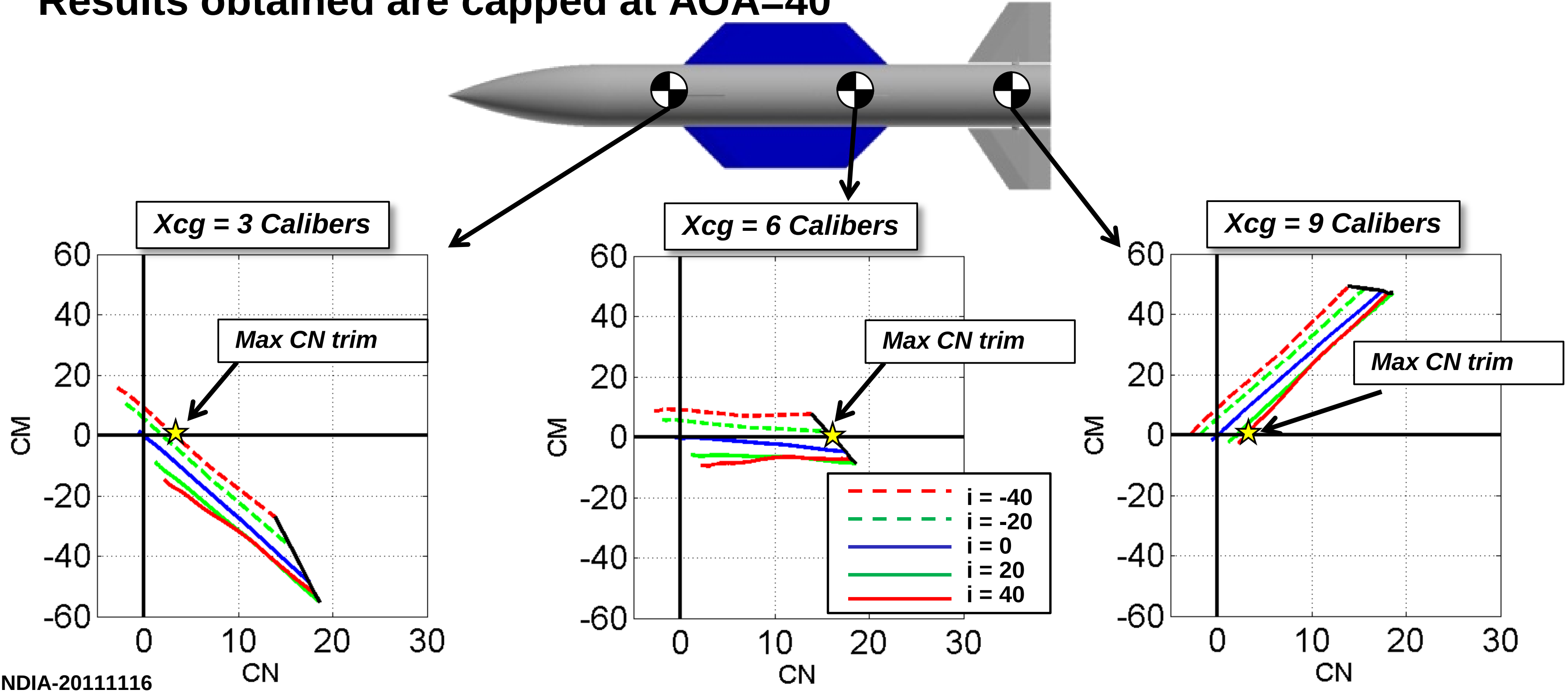
-20° fin deflection



-40° fin deflection

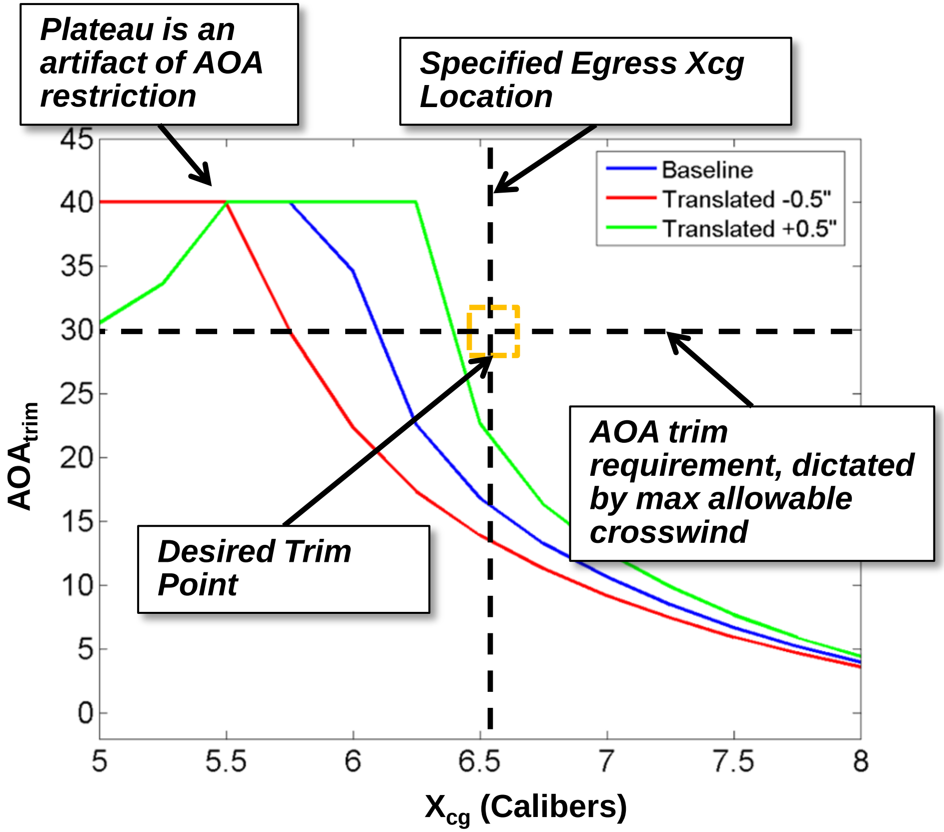
Basic Stability Analysis

- For a given configuration CN/CM carpet plots generated using fin increment maps
- Shifting Xcg results in a rotation of the carpet plot (Xcg measure from nose tip)
- Basic stability trim occurs at CM=0.0
- Results obtained are capped at AOA=40°



Egress Optimization

- Egress conditions are modeled at a freestream Mach number of 0.30
- Xcg is measured in calibers from the nose tip
- Simplifications:
  - Plume, booster, and ship deck effects are ignored for this analysis
  - Mass properties are fixed
- Mass properties drive Xcg at egress and crosswinds drive AOA_{trim} requirement
- Moving Xcg forward increases egress stability



Plateau is an artifact of AOA restriction

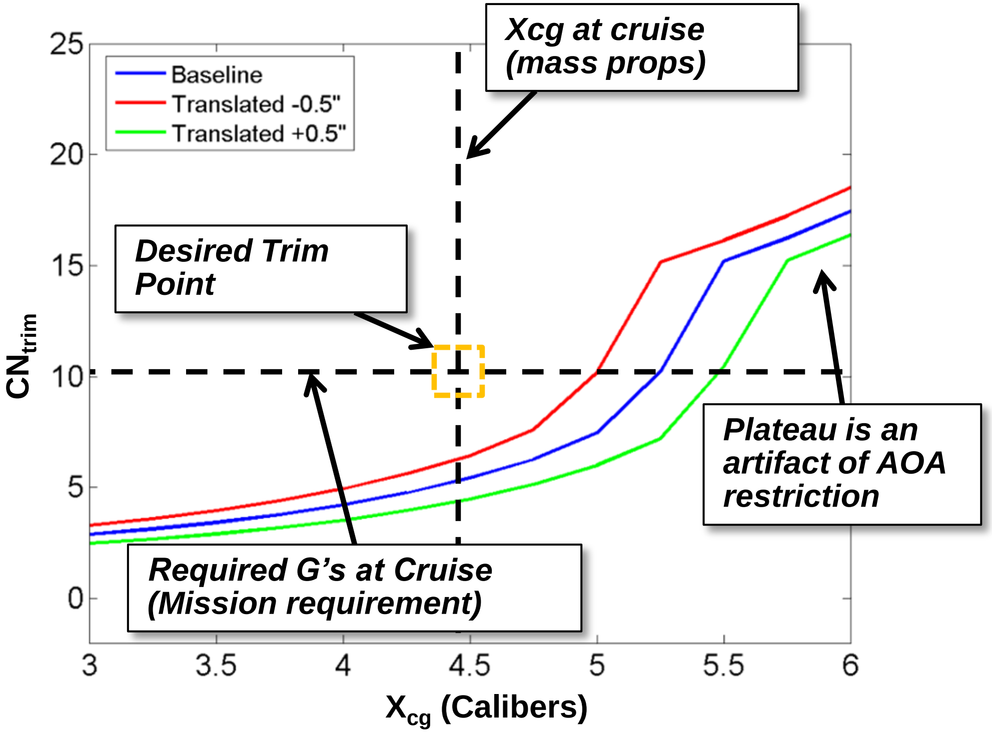
Specified Egress Xcg Location

AOA trim requirement, dictated by max allowable crosswind

Desired Trim Point

Burnout Optimization

- Cruise conditions are modeled at a freestream Mach number of 2.00
- CG location further forward due to absence of propellant/booster/etc…
- Normal force at trim, or G capability, a strong function of altitude
- Typically shifting Xcg location further aft results in higher G capability
- Trade-off exists between egress and burnout conditions "Can't have your cake and eat it too!"



Xcg at cruise (mass props)

Desired Trim Point

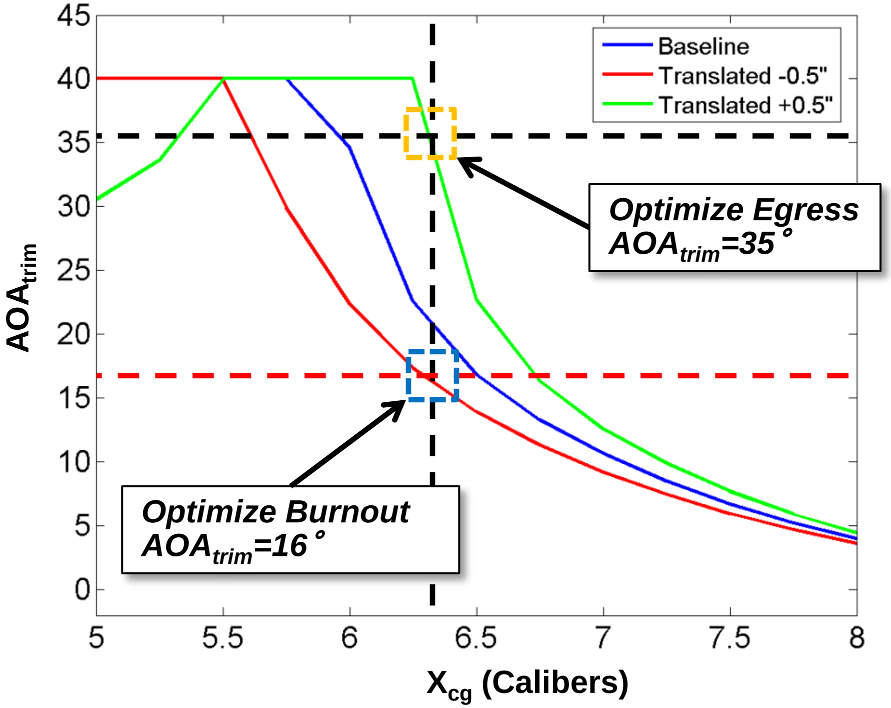
Required G's at Cruise (Mission requirement)

Plateau is an artifact of AOA restriction

Egress/Cruise Trade

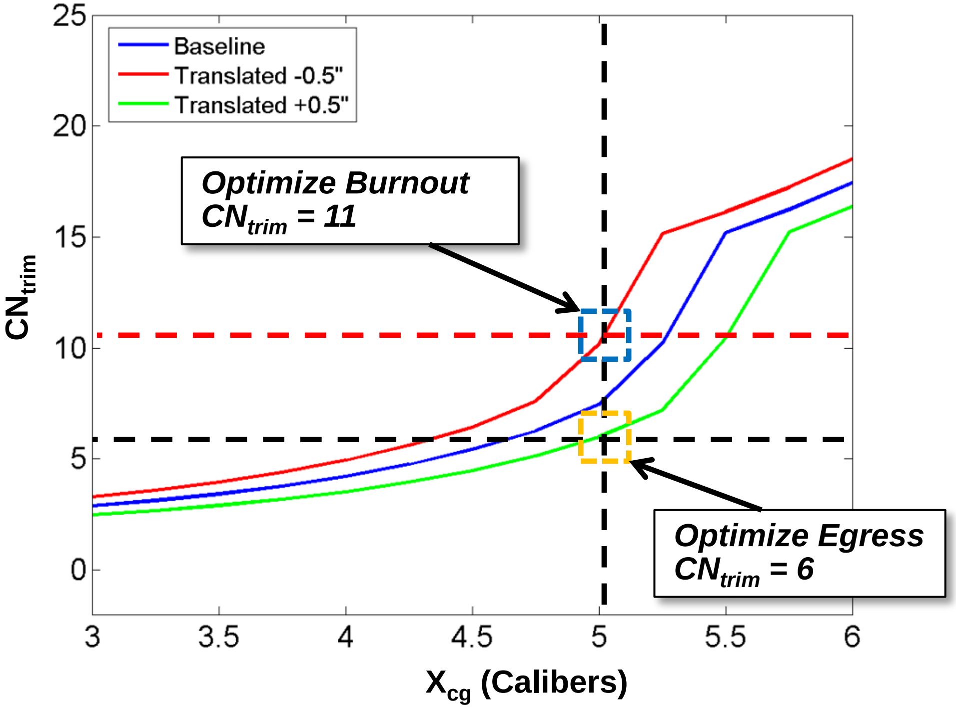
- Optimizing for maximum egress stability results in lower G capability … and vice versa

- In the plots shown:
  - Optimum egress config yields AOA_{trim}=35 and CN_{trim} = 6
  - Optimum burnout config yields AOA_{trim}=16 and CN_{trim} = 11



Optimize Egress AOA_{trim}=35°

Optimize Burnout AOA_{trim}=16°

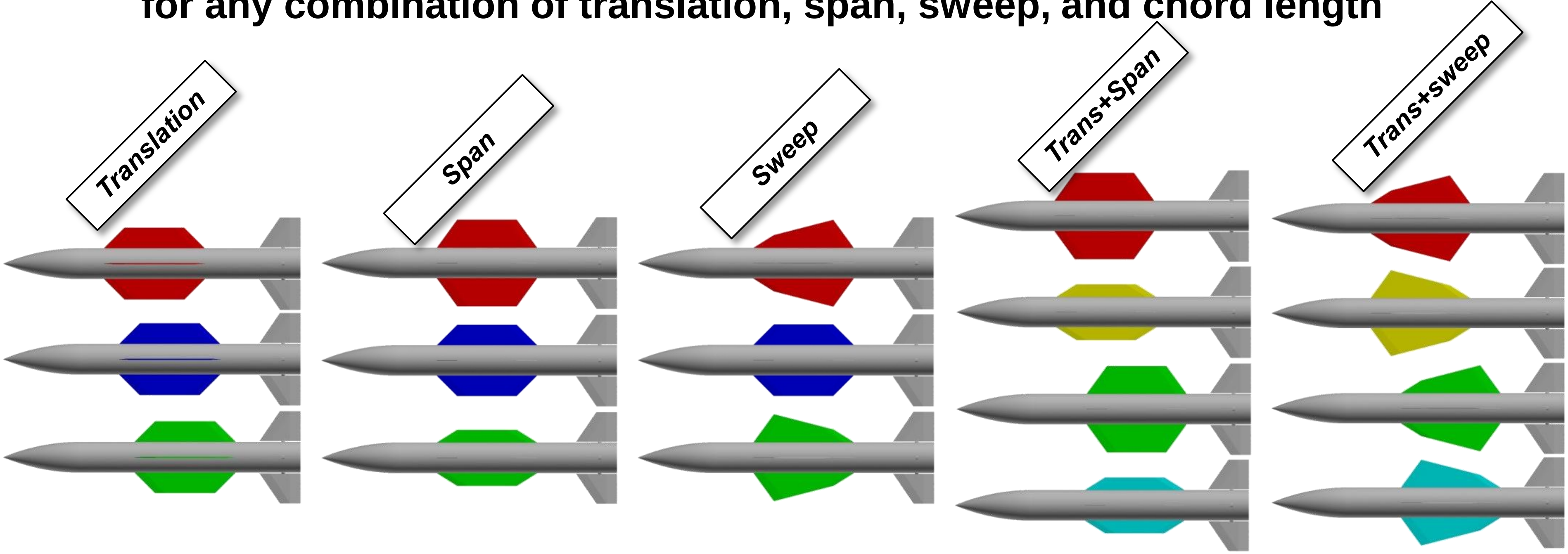


Optimize Burnout CN_{trim} = 11

Optimize Egress CN_{trim} = 6

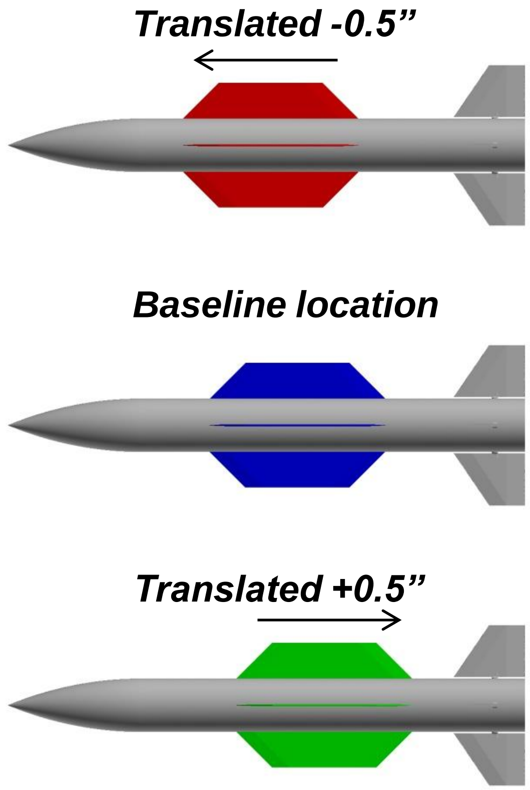
Static Stability Results

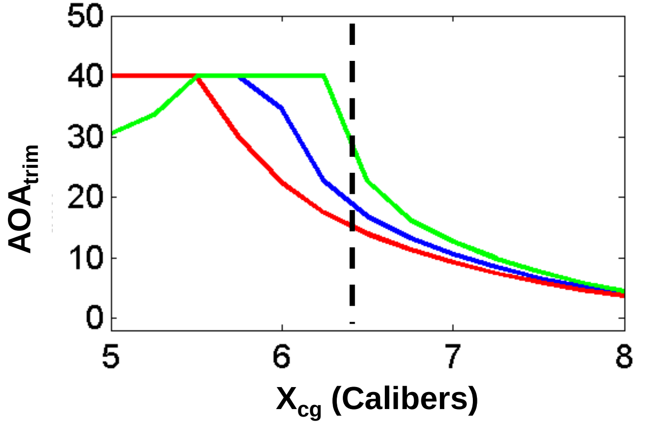
- **Limited to families of configurations for this presentation**
- **Completed subsonic and supersonic continuous pitch sweeps to collect necessary data to examine effects of translation, span, sweep, chord, translation+span, and translation+sweep on trim characteristics**
- **Assuming linear trends between configurations we can map the space for any combination of translation, span, sweep, and chord length**

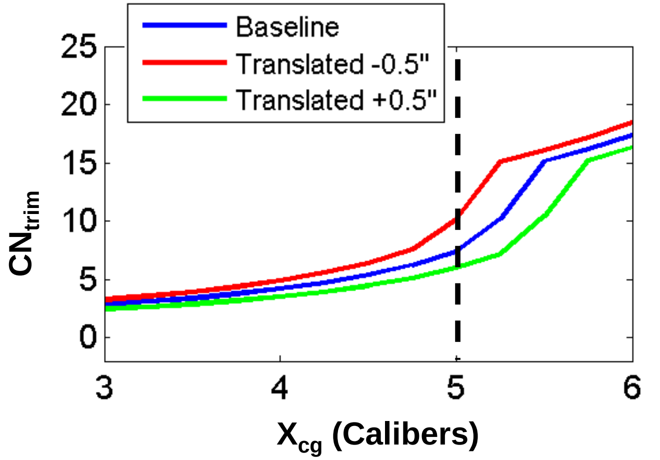


Dorsal Translation

- **Translating dorsals directly shifts Xcp**
- **Trends caused by Xcg being ahead of the Xcp location**
- **Egress effects:**
  - **Shifting dorsals aft *increases* egress stabilty**
- **Burnout Effects:**
  - **Shifting dorsals aft *decreases* maneuverability or G capability**



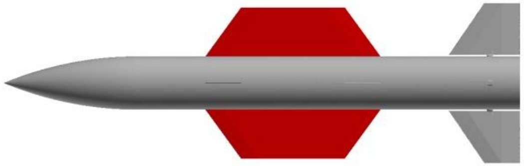




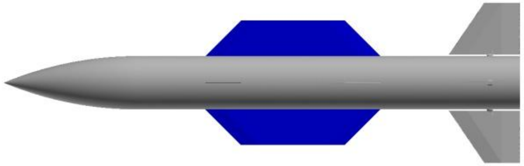
Span Increase/Decrease

- **Egress effects:**
  - **Decreasing span increases egress trim capability**
  - **Tail fins produce majority of lift in the reduced span configurations and therefore shift Xcp aft**
- **Burnout effects**
  - **Increasing the span results in an increase in G capability at cruise**
  - **Small effect on G capability for most CG locations except those > 5**

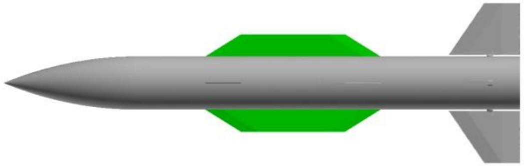
Span Increase +0.25”

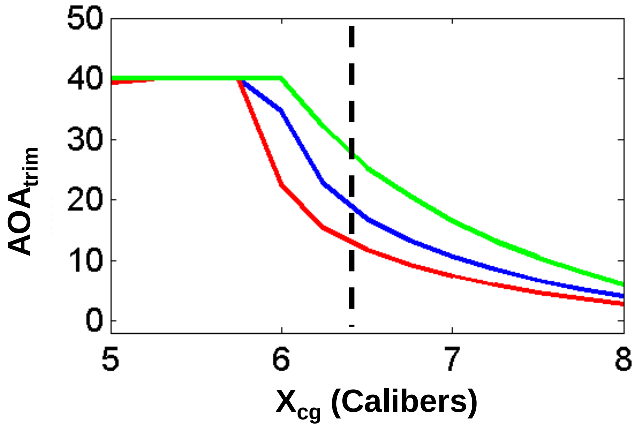


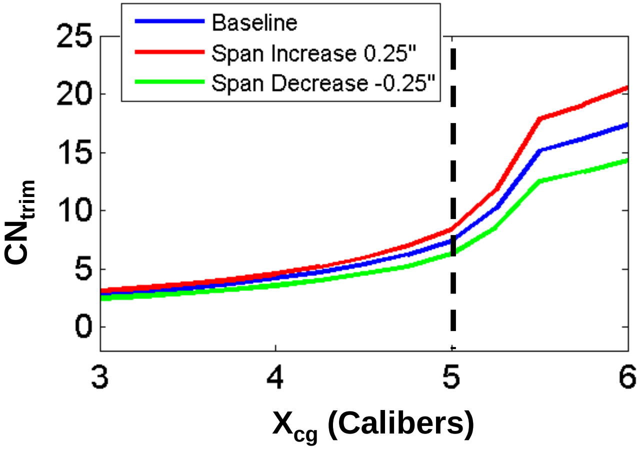
Baseline Span



Span Decrease -0.25”



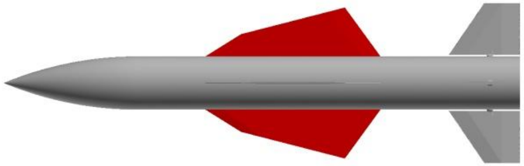




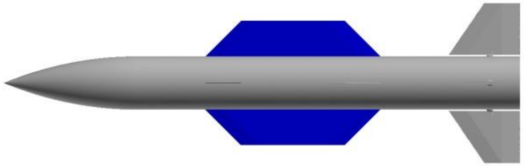
Dorsal Sweep

- **Egress effect:**
    - **Little effect on egress for these configurations**
    - **Sweeping dorsal aft shifts Xcp aft and slightly improves egress trim capability**

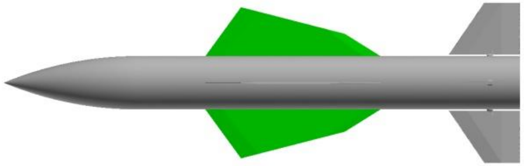
- **Burnout effect:**
    - **Marginal improvement in G capability at Xcg 4.5-5.5**



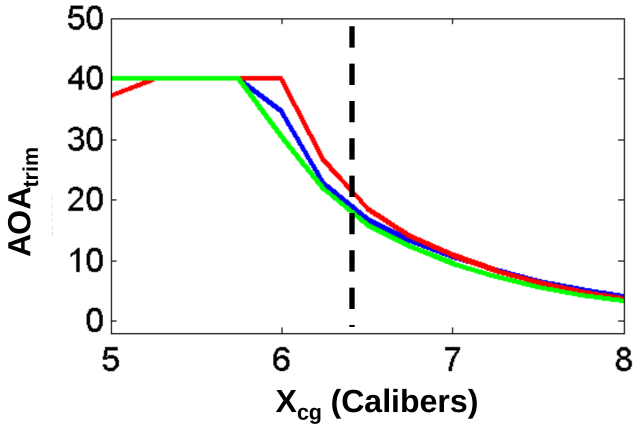
Aft Swept

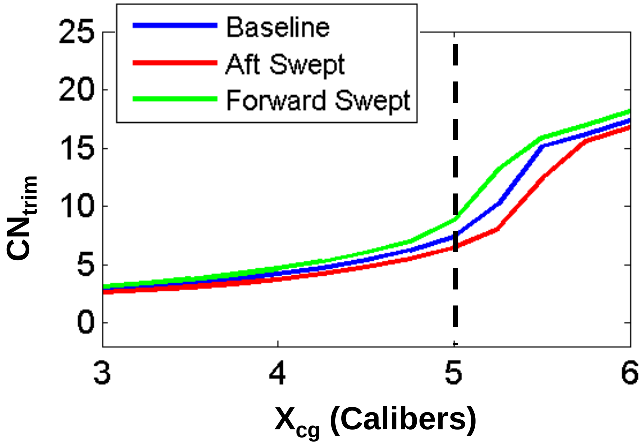


Baseline



Forward Swept

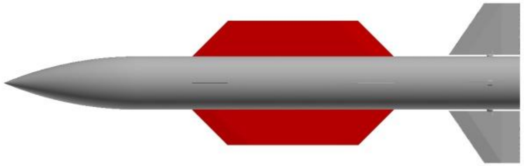




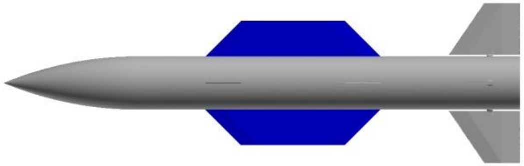
Dorsal Chord Expansion/Contraction

- **Egress effect:**
  - **Contracting the dorsal chord results in a large aft shift in Xcp thereby significantly increasing trim AOA**
  - **Expanding the chord marginally reduces trim capability**
- **Burnout effect:**
  - **Increased “roof top” in CN_{trim} but little change for remainder of Xcg positions**

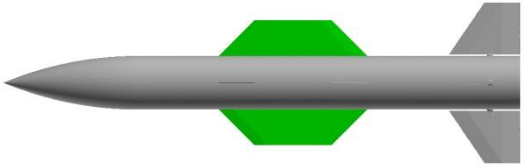
Expanded +0.5”

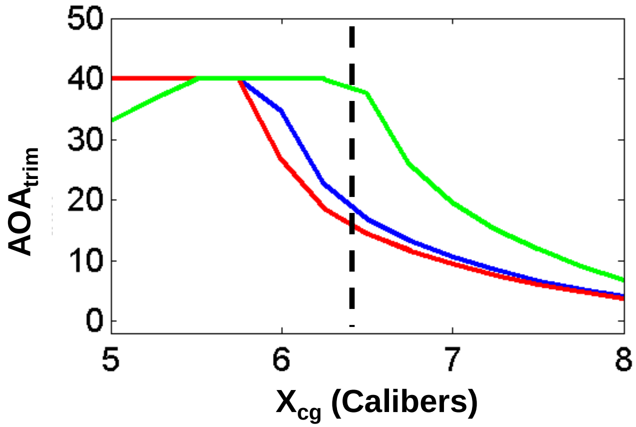


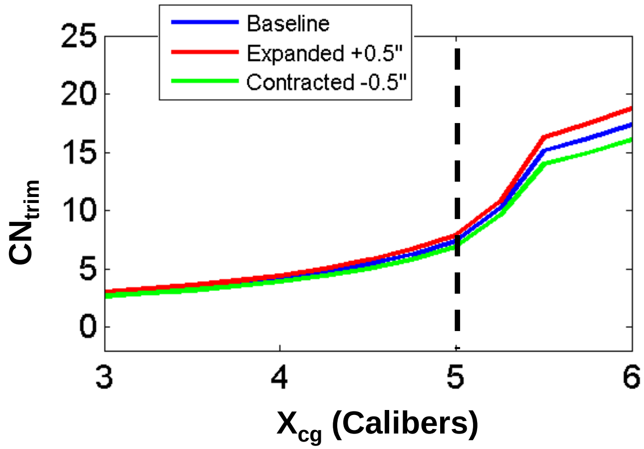
Baseline



Contracted +0.5”

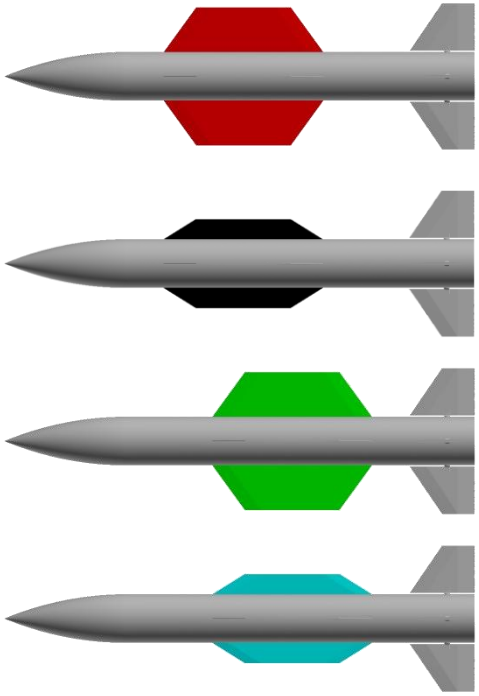


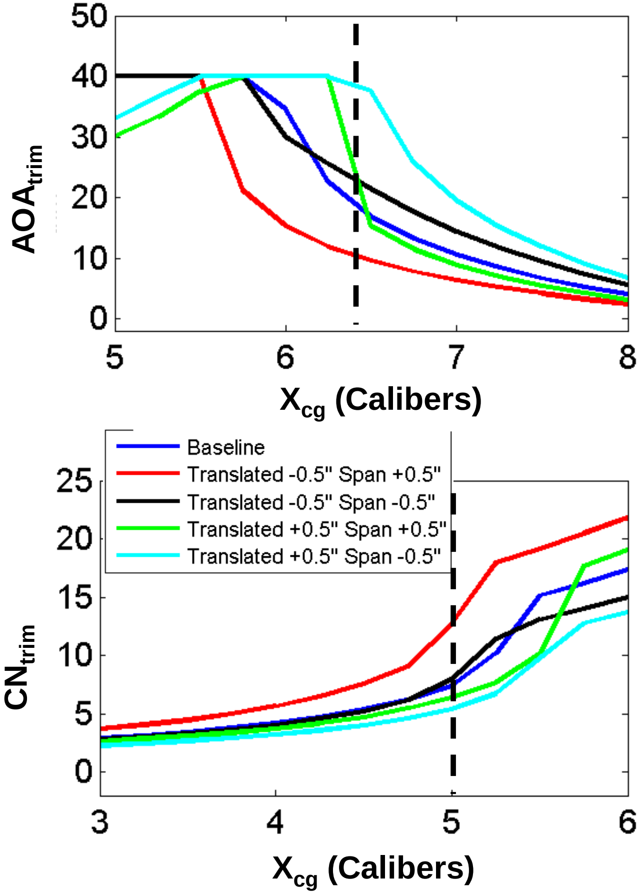




Translation and Span

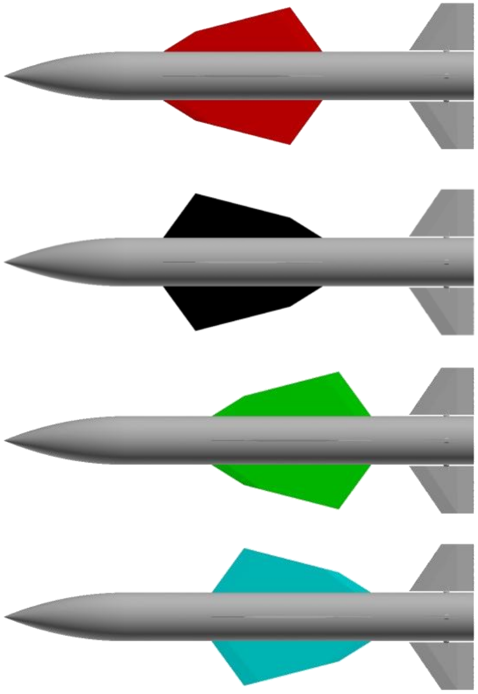
- **Egress effect:**
  - **Aft translation + decrease in span exhibits the best egress trim characteristics**
  - **Depending on mass properties one could argue the benefit of aft trans + increased span**
- **Burnout effect:**
  - **Largest increase in G capability realized in forward trans + increased span**

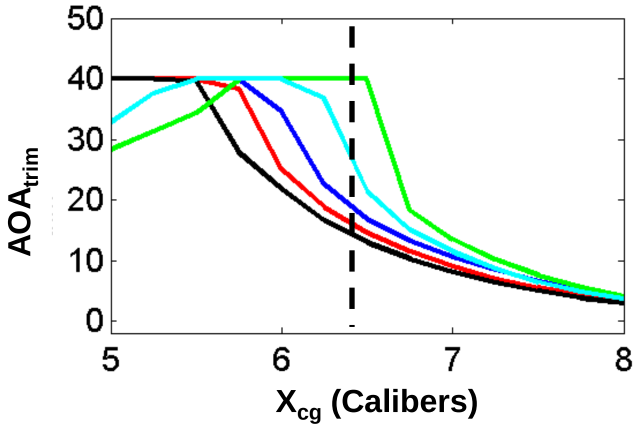


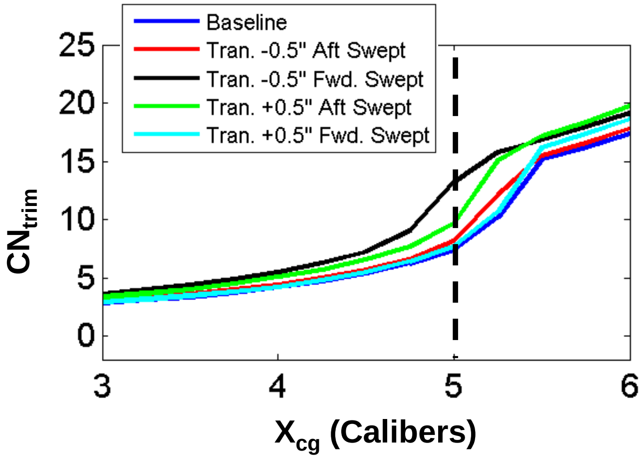


Translation and Sweep

- **Egress effect:**
  - Trans. + sweep can substantially improve/worsen trim AOA at egress
  - Aft shift + aft sweep → largest increase in trim AOA (shifting Xcp as far aft as possible)
  - Forward shift + forward sweep → largest decrease in trim AOA
- **Burnout effect:**
  - Forward shift + forward sweep results in improvements in maneuverability

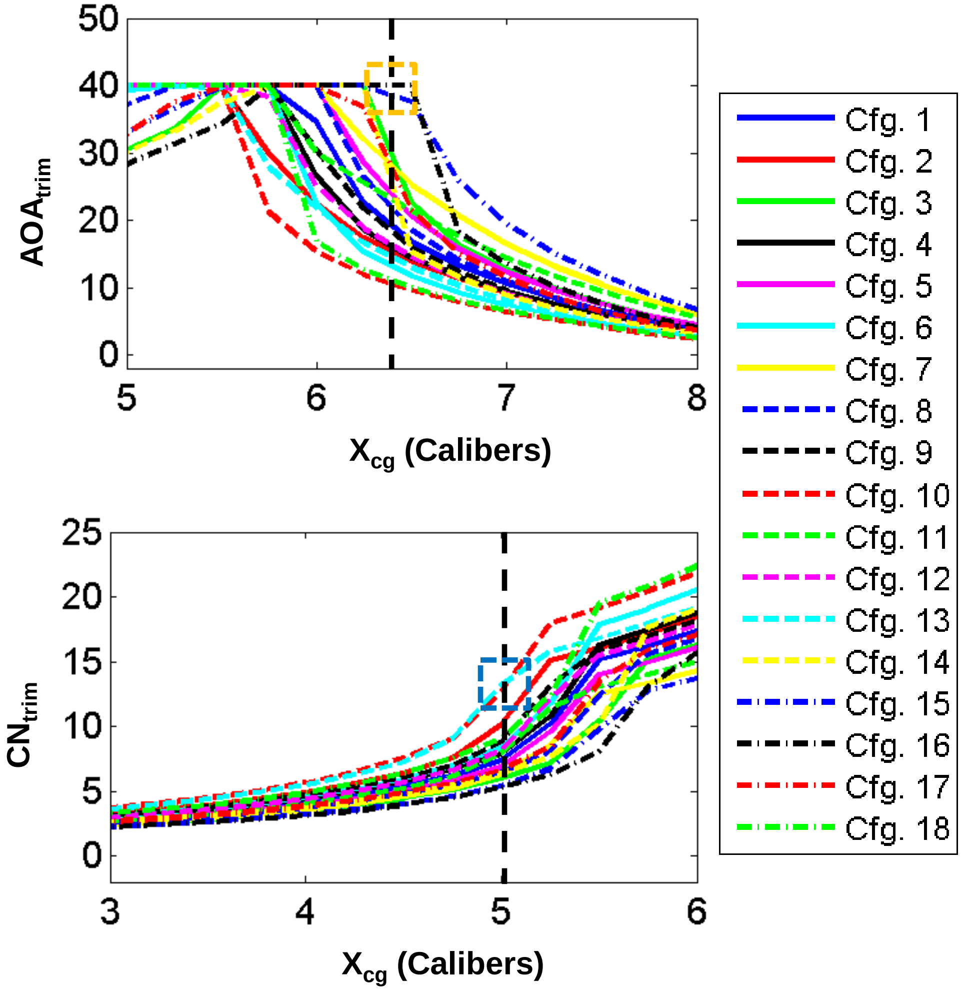






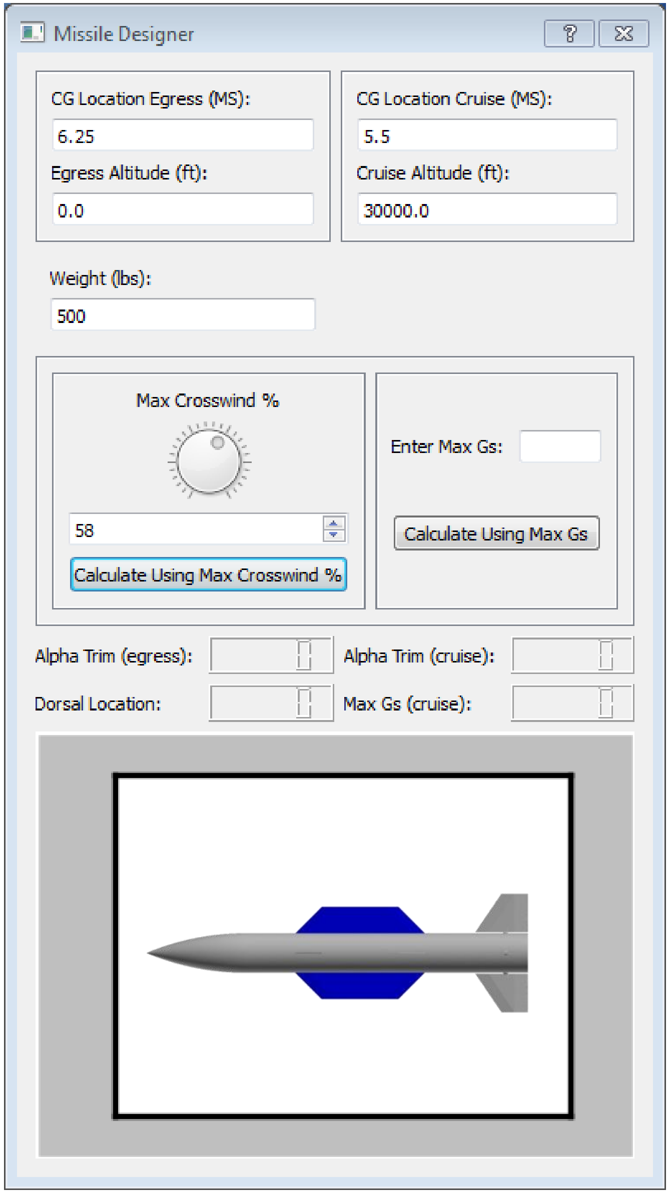
Results Summary

- **Eighteen out of 25 configurations highlighted**
- **Total of 58 continuous pitch sweeps completed**
  - **25 for egress**
  - **25 for cruise**
  - **8 pitch sweeps for fin increments**
- **Can drive egress and cruise trim characteristics by sizing dorsals appropriately**
- **Trades can be performed for each dorsal configuration**
- **At given Xcg locations:**
  - **Configs 15 &16 best at egress**
  - **Configs 10 &13 best at cruise**
- **Tremendous amount of data that can be difficult to digest …**



Corvid MIssile DESign Tool (MIDESTO)

- Missile design tool developed to expedite the data mining process
- Inputs:
  - Mass properties (Egress and burnout CG locations and weight)
  - Mission requirements (Max crosswinds at egress or max G's at burnout)
  - Burnout altitude
- Performs linear interpolations between given results to provide optimal dorsal configuration for given mission requirement and mass properties
- Useful tool to have at design round-table discussions
- Currently limited to one design parameter (chord, sweep, location)
- Work in process to combine these



CG Location Egress (MS): 6.25
Egress Altitude (ft): 0.0
CG Location Cruise (MS): 5.5
Cruise Altitude (ft): 30000.0
Weight (lbs): 500
Max Crosswind %: 58
Enter Max Gs:
Alpha Trim (egress):
Alpha Trim (cruise):
Dorsal Location:
Max Gs (cruise):

Summary

- **Focused aerodynamic database generated for a missile-like configuration derived from the modified ANF**
- **Aeromaps were expedited using the Corvid mesh deformation capability**
- **Static stability analysis performed for each configuration with trends highlighted for various dorsal shapes**
- **Egress/cruise optimization trade-offs discussed**
- **Corvid missile design tool, MIDESTO, utilized to rapidly process stability results given various mass properties and mission requirements**

Future Work

- Exploit the full potential of the mesh deformation capability by automatically driving designs to the optimal configuration
- Identify a fitness function which can drive an automated optimization (“submit and forget”)
- Identify ways in which we can generalize this process for other design changes (i.e. tail fin changes, rocket motor diameter, etc…)

Acknowledgements

- Thanks to the aerodynamics departments at Johns Hopkins University Applied Physics Lab and Raytheon Missile Systems for their guidance on the topic of missile design

Questions?