

***Rapid Euler CFD For High-Performance
Aircraft Design***

***Final Report
NASA Langley Research Center
Contract NAS1-96014***

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Chart Number

Outline



- Motivation
- Configuration
- Resources
- Metrics
- Results
- Falling Leaf
- Discussion
- Future Efforts

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The goal here was to present one approach to rapid CFD for S&C using an unstructured inviscid method, in order to eventually assess S&C properties as early in the design process as possible. Specific results are presented regarding time, accuracy (as compared to a baseline wind tunnel database) and simplicity for the user. For COMSAC, it's more important to talk about the "specifications" required by Advanced Design and S&C, as well as how the CFD results can be combined for envelope evaluation.

Motivation



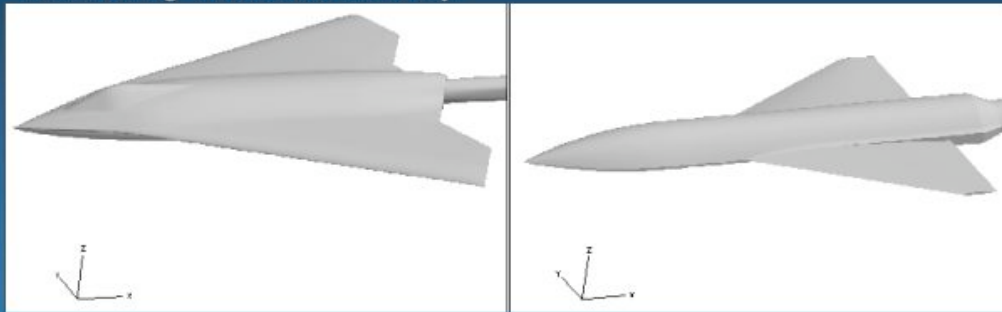
- **Original:**
 - Objective: Rapid Euler CFD To Advance High Performance Aircraft Design.
 - Results: Time, Accuracy, And Ease Of Use.
 - Goal: Routine CFD Usage In Design.
- **Current:**
 - This Project Included Generated Standards Required For CFD To Be Useful To Advanced Design And Stability & Controls.
 - This Project Also Combined CFD Results To Evaluate An Envelope For Stable Flight.

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Two configurations were considered, the tailless delta wing (“ICE”) configuration and the MTVI configuration. Each configuration actually has two vortices, with the second vortex on the ICE model starting at the change in camber and thickness where the fuselage and the wing blend. Accurate CFD analysis on vortex-dominated flows requires resolving the vortex core; adaptive methods can focus in on the core, but may need to be setup to do so. Vortex breakdown will also be significant in a vortex-dominated flow.

Configurations

- Tailless Delta – “ICE”
 - Blended Fuselage/Cockpit, Broken Trailing Edge.
- MTVI
 - Delta Wing With Chined Body



- Key to Vortex Solution Is Resolving the Core.
 - But How to Adapt to the Core?
- Vortex Breakdown
 - High $\alpha \geq 24^\circ$ and Is Aggravated by Large β (Unsteady).

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Many CFD cases were run on the two configurations to complete the run matrices.

Run Matrix



MTVI, α -Sweep, Inviscid									
β	α								
0		12		20		30		40	
2	6	12	16	20	25	30	35	40	45

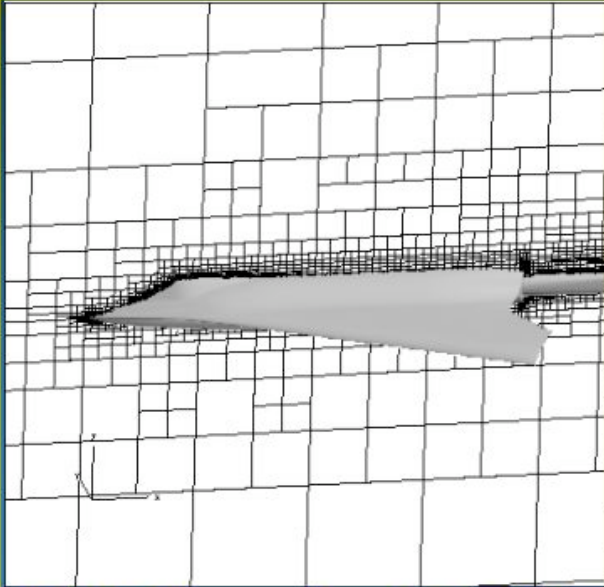
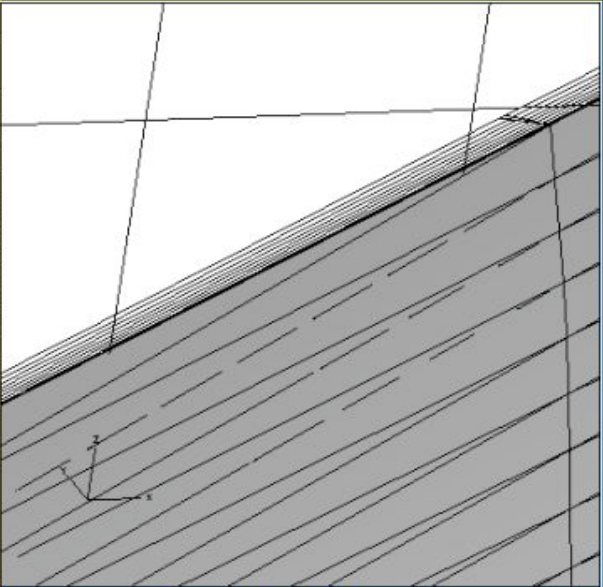
Tailless Delta, α -Sweep, Inviscid									
β	α								
0	0		10	15	20				30
5	0		10	15	20				30
10	0	5	10	15	20	22	24	26	28
20	0	5	10	15	20	22	24	26	28

Tailless Delta, β -Sweep, Inviscid									
α	β								
20	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	

Tailless Delta, Viscous			
β	α		
10	22	24	28
20	22		28

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Two versions of Splitflow were used; the parallel version does not support the hybrid grids made from prisms extruded from the surface triangulation. The parallel version is still used today on engineering workstations, SGI Origins, and parallel clusters.

Codes and Equipment	
Omnigrid Splitflow Parallel	Hybrid Splitflow Vector
	
SGI, HP/Convex, Cray J-90 (PVM)	Cray J-90 (Vector)

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The contract effort was divided into two parts, CFD analysis and metrics. The CFD analysis used solution-based adaptation, checked for grid convergence as part of the data comparison, and considered grid resolution as part of the study. Metrics were specified by representatives from two groups, Preliminary Design and Stability & Controls, for the time required, accuracy required, and some measure of the ease of use.

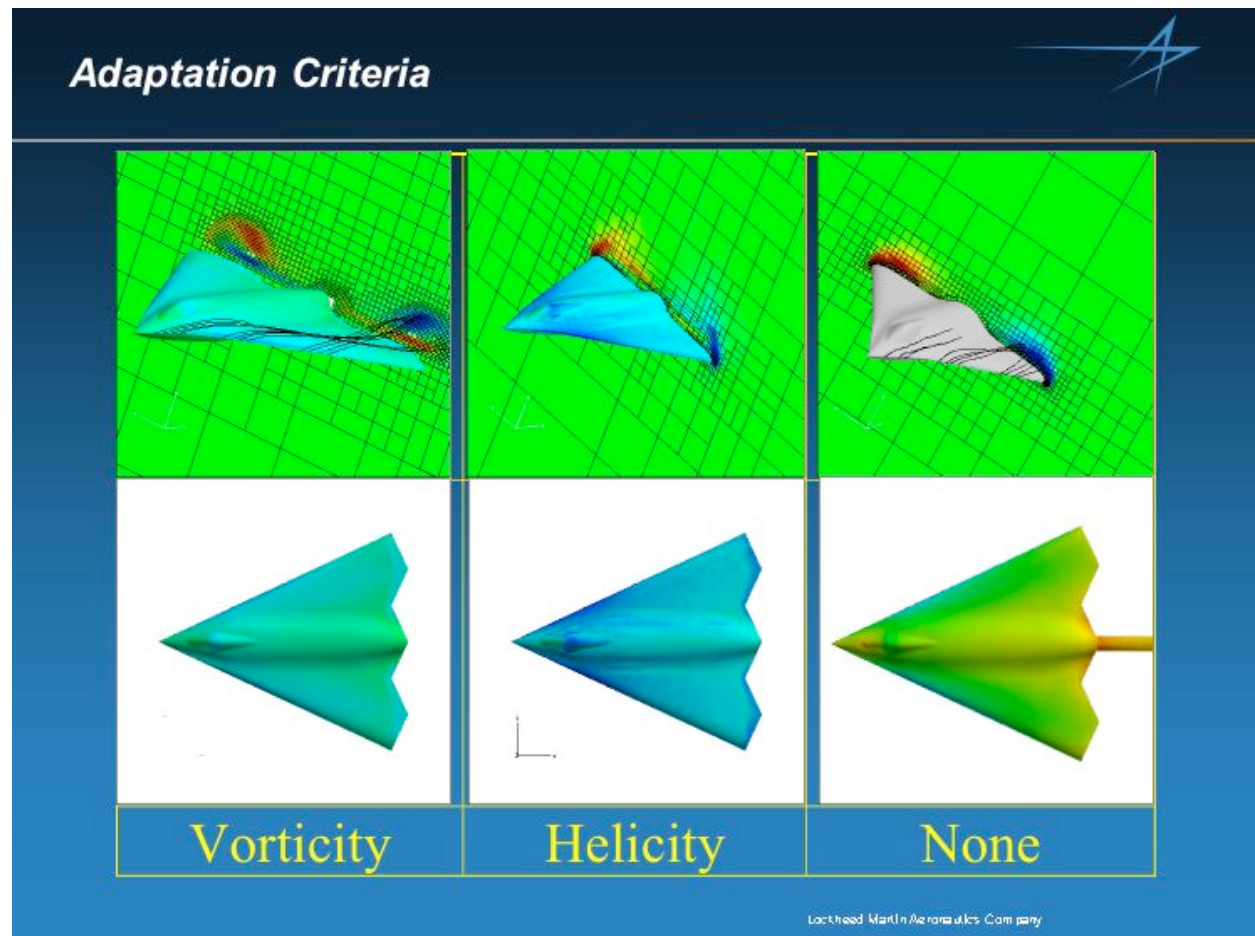
Runtime and Metrics Introduction



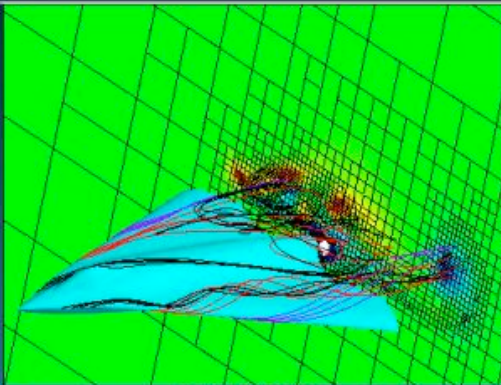
- CFD
 - Solution Adaptation
 - Grid Convergence
 - Leading-Edge Resolution
- Preliminary Design and Stability & Controls
 - Time
 - Accuracy
 - Ease of Use

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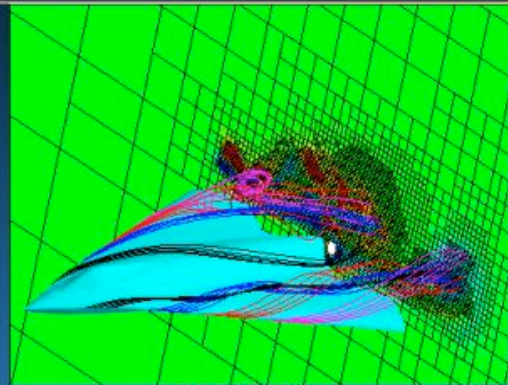
“You cannot solve what you do not resolve.”—Steve Karman. Solution-based grid adaptation gives the grid the opportunity to adapt to the flow solution as the solution progresses. The grid itself helps set what kinds of flow solutions can be modeled, so it is critical to have an appropriate grid. The three plots here show an example of adapting to vorticity, helicity, or not at all, and they show dramatically different results. Traditionally, helicity was used by Splitflow to adapt on vortical structures—the concern was that vorticity would simply add cells to the boundary layer. Unfortunately, helicity does not highlight the vortex core, which is critical for modeling a vortex, and the field value of helicity itself fall to near-noise levels after a vortex burst. Together, those effects make considering raw vorticity critical to adapting to vortex-dominated flowfields.



Tailless Delta wing, Grid Convergence



400K Cells



800K Cells

- 400K Cells
- A Few Cases Grid-converged At 400K And 700K+ Cells.
- No Noticeable Improvement Found In Matching WT Data With The Larger Grid (Any Useful Euler Data Can Be Found At 400K Cells).
- Results Suggest That 400K Cells May Be A Minimum, Due To Necessary Resolution Of The Vortex Core Off The Surface.

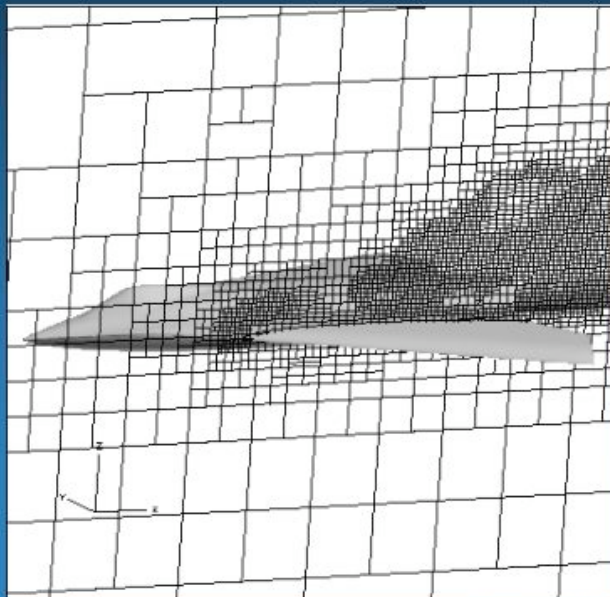
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Sufficient leading-edge resolution is often critical to setting up the proper flowfield and accurately computing the aerodynamic characteristics on the suction-side of the vehicle. However, the gradients of classic analyzed variables (e.g. pressure, Mach number, density) are not very large compared to those inside of vortices or near shocks. This results in most of the solution-based adaptation going into those areas, not to the leading edge.

Leading Edge Resolution

- Leading-Edge Resolution Is Unimpressive; Adaptation Criteria Favors Adding Cells to the Vortices.

$$M_{\infty} = 0.3, \alpha = 24^{\circ}, \beta = 10^{\circ}$$



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Metrics are one of the real topics of discussion here. Metrics were developed by consulting with specific colleagues in the areas of Advanced Design and Stability & Control. The metrics presented here could be considered a start for a discussion of more general standards.

Metrics



Metrics Were Required For:

- Time
- Accuracy
- Ease Of Use

With Input From Two Target Groups:

- Preliminary Design
- Stability & Controls

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Criteria for evaluating CFD for Preliminary Design were produced by discussions with individuals involved in Preliminary Design. At this point, the data presented only represents a few opinions on the matter, but it's a start.

Preliminary Design Criteria (Time)



- Preliminary Design Focuses On The Cruise Point.
 - One Polar Not Enough
 - Depends On Configuration
 - Need Extra Points For High Lift Devices
 - 3 -10 For Flap Schedule And Trim Data
 - 3 Flap × 3 Tail × 3 Leading Edge Flap
 - Possibly Other Ways To Get Tail Data ... Still Leads To A Lot Of Data Required

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Preliminary Design Criteria (Time) (continued)



- Current Approximate Methods (1998) Require About One Week to Do One Aerodynamic Analysis.
 - The Codes Are Fast
 - Most of the Time Is Spent on Setup, Calibration, and Analysis
- Aerodynamics Wants a Full Matrix in 24 Hours
 - So Need One α Sweep Per Hour

**At This Point, CFD Would Become the Preliminary
Aerodynamic Design Tool**

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Preliminary design is focused on generating the necessary lift at the minimum drag.

Preliminary Design Criteria (Accuracy)



- Priority For Preliminary Design Is Drag: C_D
 - ΔC_D Might Be Good Enough
- Really Need Lift, Drag, Pitch Moment (C_L , C_D , M_y)
- At A Given C_L , We Want
 - $C_D \pm 5\%$ Below Polar Break (Cruise)
 - $C_D \pm 10\%$ Above Polar Break (Maneuver)
- $C_{D0} \pm 5\%$

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Preliminary Design Criteria (Ease of Use)



- CFD Tools Often Require Many Training Hours
 - Documentation May Not Be Clear
- CFD Tools Often Have Too Many Parameters To Tweak
 - But Not Enough Parameters To Control the Solution?
- Need Parameter Sets That Work Consistently For A Given Class Of Problem
 - Prefer More Automated Analysis
- A GUI Would Be Nice
 - Perhaps An Expert-Type Input Checker With A Model To Help Set Parameters

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CFD tools are very useful already, but there are still needed improvements. The user interface is the weak spot, both in getting control information into the code, and in getting configuration information in. These weaknesses affect other codes, too, not just Splitflow, which is very dependent on a “good” surface mesh.

Preliminary Design Criteria (Conclusions)



- Current CFD Tools Produce Useful Answers
 - But Still Need Improvements
- Namelist (Unchecked) Type Input Problems Can Cause Long Delays
 - Formatted Input Is Even Worse
- Need A Way To Reduce Grid Problems
 - Surface Meshing Is Still An Art
 - Automatic Cleanup, Something That Guarantees A Good CFD Ready Surface Mesh
 - Can't Always Refine Out Of A Jam, Need To Fix Problems Up Front
 - Cartesian Methods Like Splitflow Have A Particular Problem With “Split” Cells (Thin Geometry)

Exactly As With Airplane Design in General, We Need a Way to Fix Problems Early in the Process

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S&C requirements are a little different than Advanced Design, which really focuses on performance. The really tough one is the “within two degrees of zeroes.” When plotted, that band really necks down, and when evaluated, it’s very difficult to accomplish with the methods in this presentation.

S&C Criteria



- S&C Criteria Based on *Proceedings of the Non-Linear Aero Prediction Requirements Workshop*, Edited by Michael J. Logan, NASA Langley Research Center, December, 1993.
- Key Concern Is Reliable Data From a Combination of
 - Databases
 - Linear Methods
 - Higher Order Methods for Potentially Complex Configurations
- Goal Is Simplicity and Speed
 - Antithesis of Euler/NS Methods, Regrettably
- Accuracy:
 - $C_L \pm 5 - 10\%$ Attached, $\pm 10 - 20\%$ Partly Separated, $\pm 20 - 30\%$ Fully Separated
 - Pitch, Roll, Yaw-Moments $\pm 20\%$ of Data Range, Within 2° of Zeroes
 - Doesn't Cover Trim/Performance – Assumed That Once Near, the Control System Can Handle

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Runtime Metrics Discussion



- Time
 - Setup – Minimal For Splitflow, One Setup Worked For All
 - Run – Much Longer Than Anticipated
 - Rerun – Too Often Required To Compensate For Thin Wing Based Split Cell Problems, BC/Turbulence Models, Etc.
- Accuracy
 - S&C Criteria Included On Plots.
 - Focus Is On Moment Coefficients At $\beta > 0$
 - But Plotted Tighter Tolerance Of Only $\pm 10\%$ To Better Demonstrate Areas Of Desired Improvement
- Ease Of Use
 - Setup
 - Interface
 - Robustness

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Originally, results were shown for each sweep listed above. Those results are included at the end for completeness but will not be presented here.

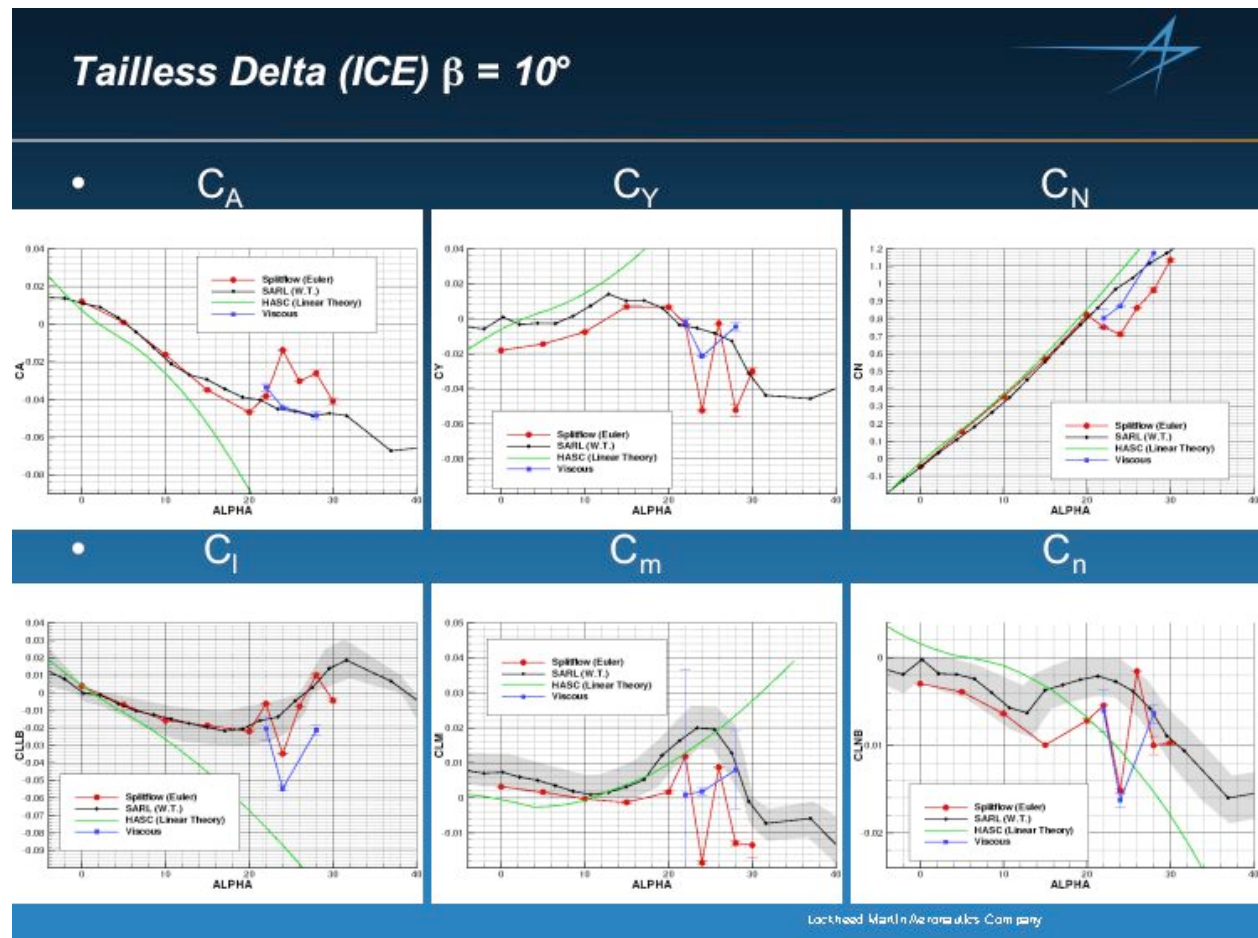
Results



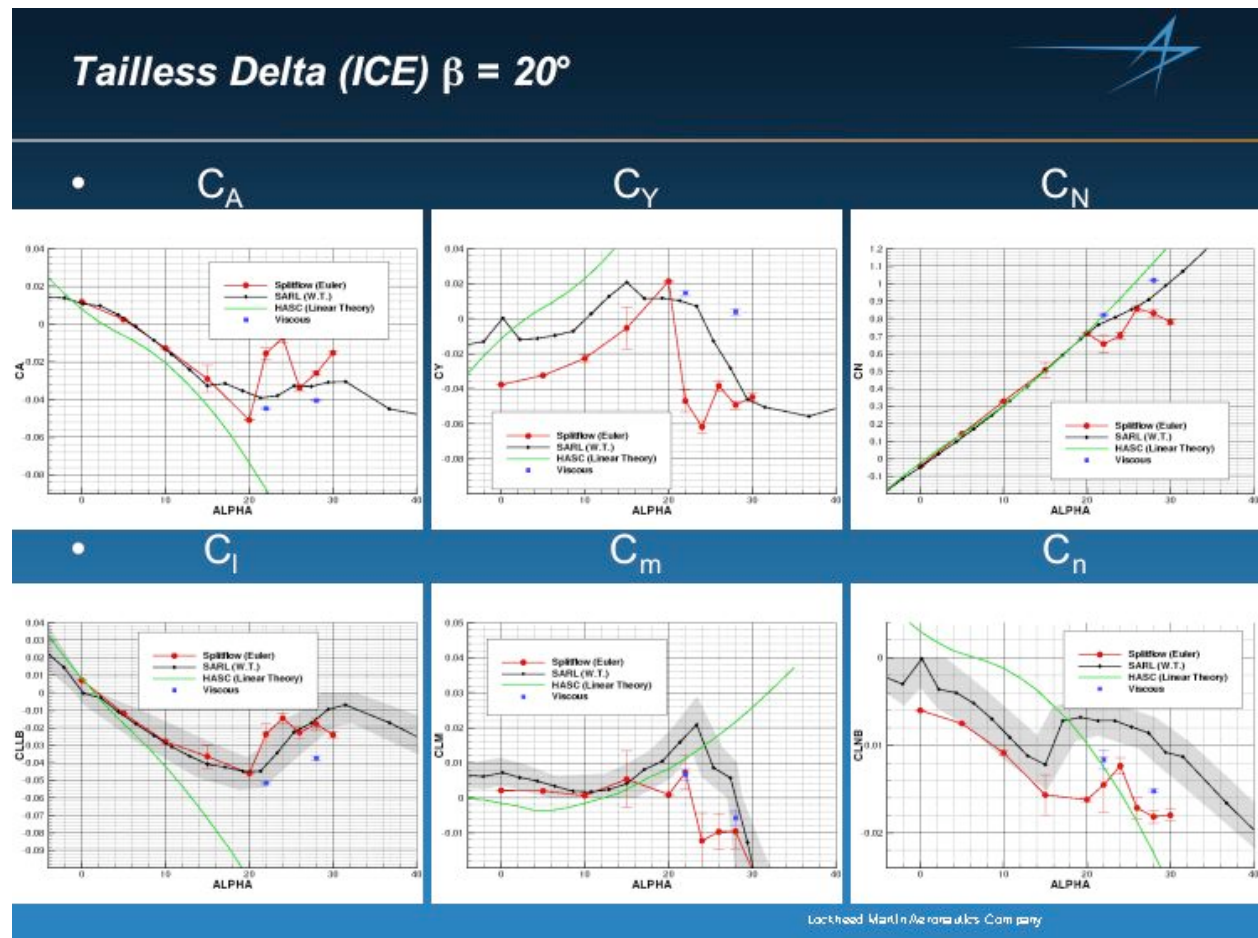
- MTVI, α -Sweep
 - $\beta = 0$
 - $\beta = 2$
- Tailless Delta, α -Sweep
 - $\beta = 0$
 - $\beta = 5$
 - $\beta = 10$
 - $\beta = 20$
- Tailless Delta, β -Sweep

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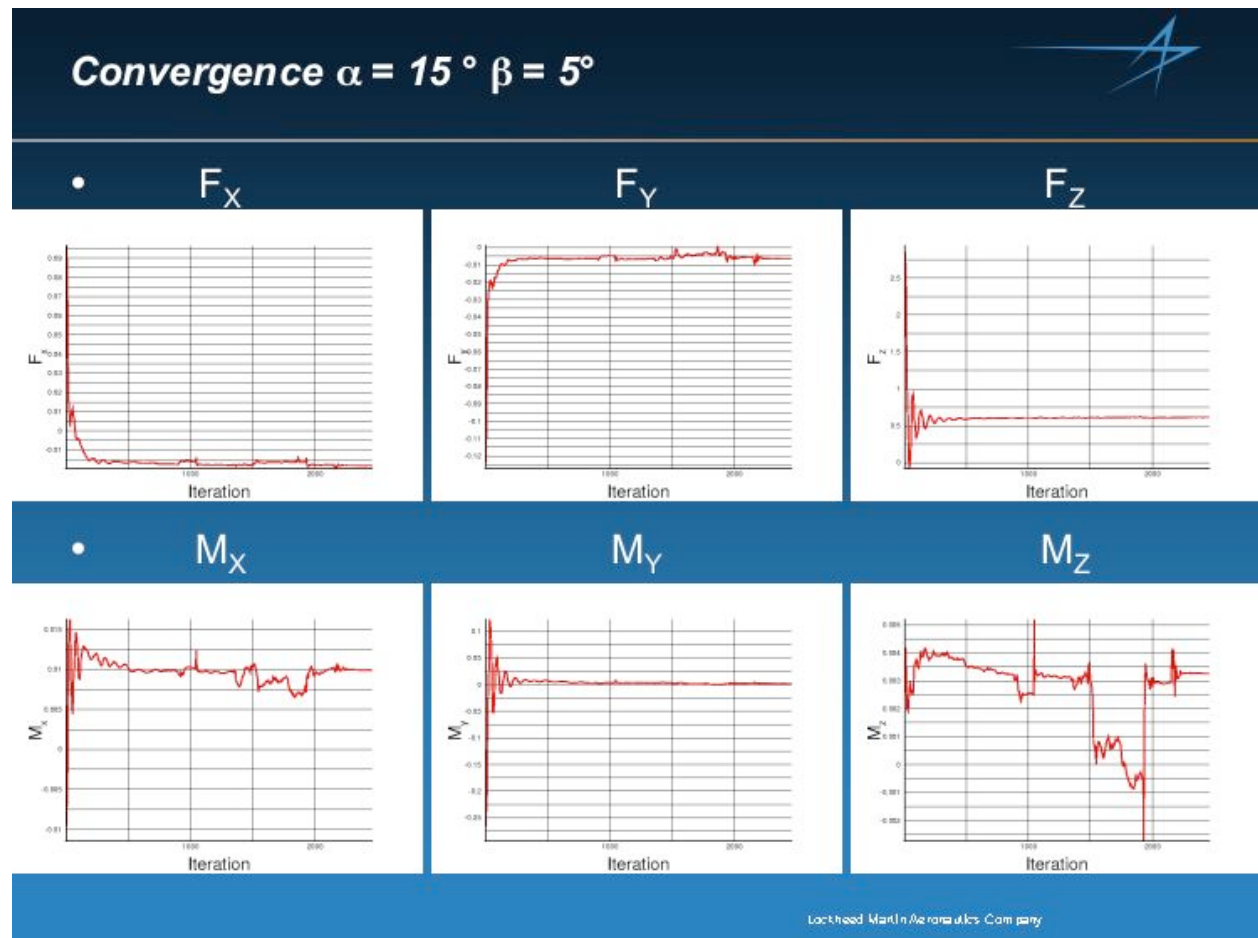
This condition is shown to highlight some of the success and some of the difficulty in this kind of CFD for S&C. Note that the results look “pretty good” until $\alpha > 20$. The error bars indicate how much change there was in the CFD results near the end of the run—note that some of these cases converged very well, just not to something that compares to the wind tunnel data.



This group of results shows just how squirrely some of the CFD analyses were. Note the pitching moment at $\alpha > 10$ in particular, even though the general comparison to the wind tunnel data looks better than it did for the $\beta=10$. Roll Pitch Yaw



This is one example of the kind of convergence experienced on these CFD runs. Note the yawing moment, whose sign is questionable. The value itself is small, however.



Some good results, some bad. At lower AOA, where 24 degrees isn't all that low, the results could be pretty useful. Above 24 degrees, with massive separation, vortex breakdown, and maybe other effects, the results were unpredictable.

Highlighted Results

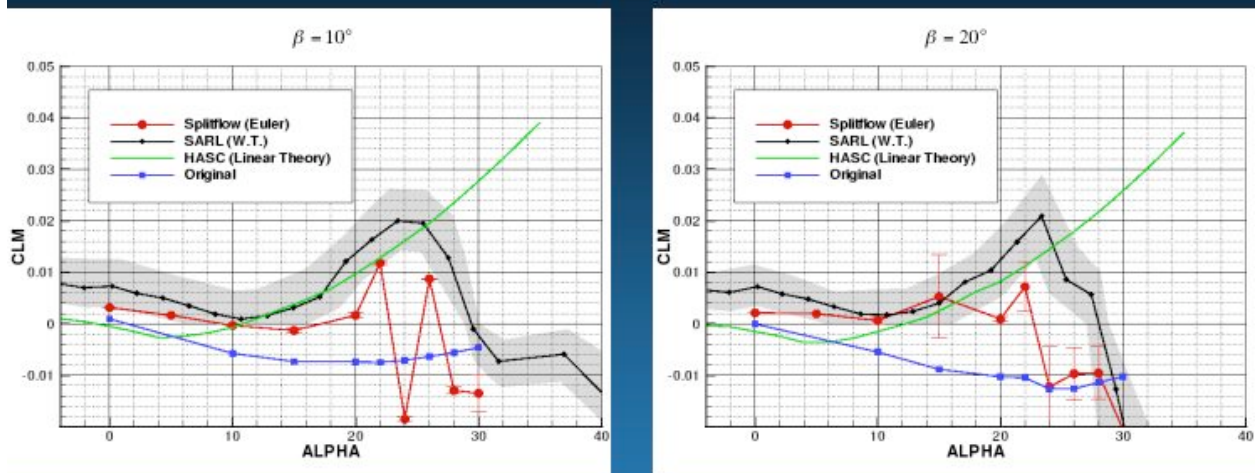


- Which Plots Look Especially Good?
 - Alpha < 24deg, Especially Roll and Yaw Moments
- Which Plots Look Especially Bad?
 - Alpha $\geq$ 24deg, Especially Pitching Moment
- Why?
 - Suspect Vortex Breakdown and Other Unsteady and Viscous Effects. Even at 700K Cells, the Vortex Cores Are Not Well Resolved.

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This shows some of the emphasis and difficulty in reproducing tunnel results. The error bars on the CFD values show how much the data was changing as the run “converged.” Note that for the left case, all of the runs converged quite well; at 24 degrees, it converged to something completely different from what was measured in the wind tunnel. At 20 degrees sideslip, beyond 14 degrees, the CFD really did not converge very well at all. One thing to keep in mind is that we do not know what the degree of variation of the wind tunnel data was.

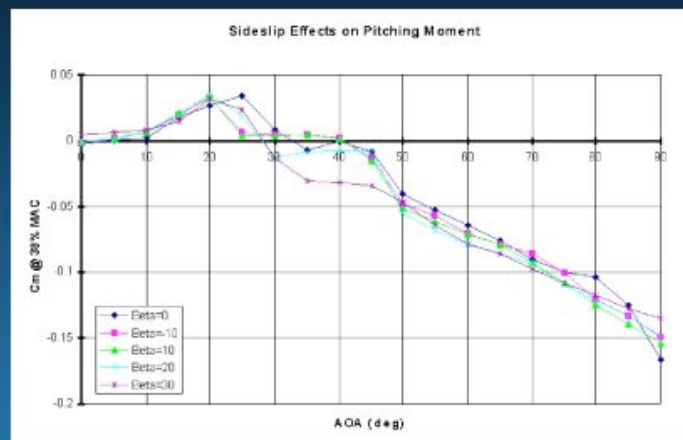
Improved Results



- “Original” Means Quick Run, Coarse (100K Cell) Grid, Four Hour Turnaround on an Octane.

This test of the same ICE model shows that some of the wind tunnel data may not be as certain as it is credited. Note particularly that the 20 and 30 degree sideslip data lie between the 0 and the +/-10 degree sideslip curves, indicating that something happens to change the pitching moment, and then it comes back.

Similar Results

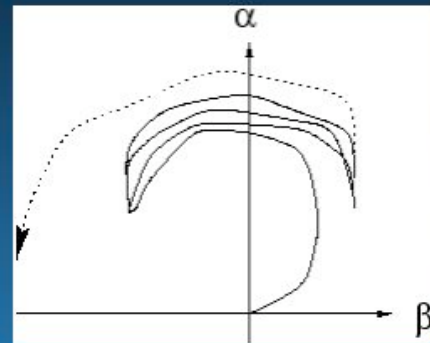
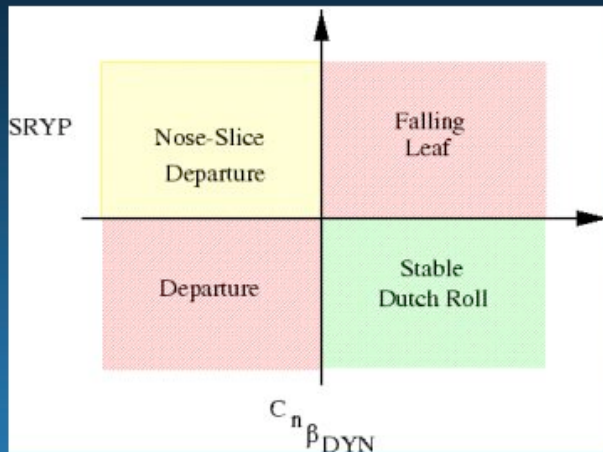


Pitching Moment Data From An ICE Contract Rotary Balance Test, 1996, Test At Bhirle Applied Research 10 Foot Vertical Wind Tunnel In Neuberg, Germany. 1/13th Scale Model, Dynamic And Static Data Collection.

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Falling Leaf is an extreme flight condition where the airplane rapidly transitions between high beta and low alpha, to high alpha and zero beta, on to high alpha and high negative beta, and then back. The Sustained Roll-Yaw Parameter measures the susceptibility to Falling Leaf, compared to simple departure or a stable Dutch roll.

Falling Leaf



- SRYP = Sustained Roll-Yaw Parameter
- Material from: Foster, John V., "Analysis of 'Falling Leaf' Motion of Class IV Airplanes, Status Update," Flight Dynamics Working Group Meeting, NAWC, Patuxent River, MD, July 27, 1995

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These are two definitions and the numeric values for the ICE configuration.

Falling Leaf Parameters



- Roll Moment: $C_{l\beta} = \frac{\partial C_l}{\partial \beta} \simeq \frac{\Delta C_l}{\Delta \beta} \simeq \frac{C_l}{\beta}$
- Yaw Moment: $C_{n\beta} = \frac{\partial C_n}{\partial \beta} \simeq \frac{\Delta C_n}{\Delta \beta} \simeq \frac{C_n}{\beta}$
- Roll Moment Of Inertia (slug*ft^2): $I_{xx} = 35,479$
- Yaw Moment Of Inertia: $I_{zz} = 110,627$
- Cross Product Moment Of Inertia: $I_{xz} = -525$

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Then, defining those two parameters, we can check for susceptibility to Falling Leaf.

Falling Leaf Criteria



- Define Dutch-roll Stability Parameter:

$$C_{n\beta_{\text{DYN}}} = C_{n\beta} \cos \alpha - \frac{I_z}{I_x} C_{l\beta} \sin \alpha$$

- And Sustained Roll-Yaw Parameter:

$$\text{SRYP} = \frac{\frac{C_{n\beta}}{C_{l\beta}} + \frac{I_{xz}}{I_{xx}}}{\frac{I_{zz}}{I_{xx}} + \frac{I_{xz}}{I_{xx}} \frac{C_{n\beta}}{C_{l\beta}}}$$

- Where Falling-Leaf Susceptibility Is:

$$C_{n\beta_{\text{DYN}}} > 0 \quad \cap \quad \text{SRYP} > 0$$

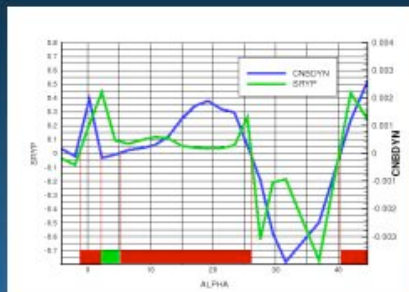
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Now we can take both the wind tunnel dataset and the Splitflow dataset, compute the Dutch-roll parameter and the “syrup” parameter, plot them together, and determine the envelope susceptible to Falling Leaf. Here, the first important thing to note is that the Splitflow envelope prediction was pretty close to the wind tunnel; the second is that an active control system would be required for all angles of attack for this aircraft. Note that the x-scales are different between Splitflow and SARL data

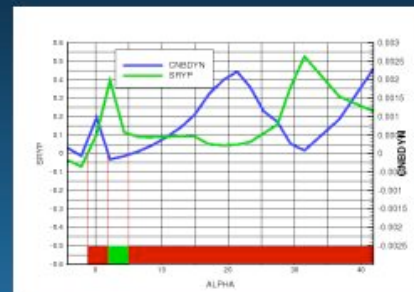
Falling Leaf Results (Tailless Delta)

- Sarl

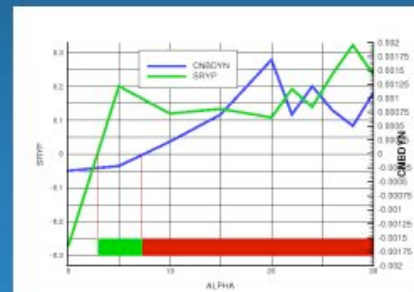
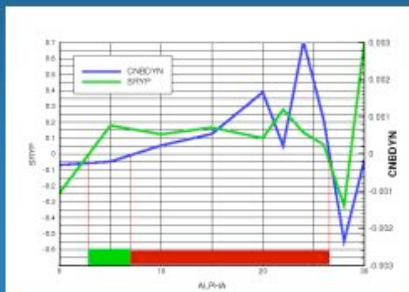
Beta=10



Beta=20



- Splitflow



- Control Augmentation Will Be Required At All Alpha.

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These methods can produce useful results, and in fact these and similar methods are already in use in the LM Aero Advanced Design and S&C community. It may not be routine yet, and each needs large run matrices that are not yet supported by our CFD tools and computer resources. Another problem is that while this project set out to find a “black box” configuration, no such thing was determined, and in many cases each flight point CFD run required individual attention. Some of the performance applies to five years ago, too. Now, a lot of this analysis can be (and is) performed, opening up these requirements to apply to complete aircraft instead of the simpler configurations (ICE & MTVI) presented herein.

Conclusions



- Much of the Desired Data Can Be Accurately Determined, but Required Larger Grids and Longer Runtime.
- S&C Desires Complete Analysis in Hours – Not Practical With Euler Methods (1998).
- Preliminary Design Wants a Solution Per Hour – Also Not Currently Practical (1998).
- No Black Boxes Here ... Any Minimum Resource Criteria Will Vary With Configuration, Flow Speed, AoA, Etc.
- Goal of Routine CFD Usage in Design Is Coming Along. Now Used by S&C, Advanced Design Has Been Using It for Some Time.

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Acknowledgements



- Vortex Analysis: Dave Darmofal and Andrew Cary
- Advanced Design: Paul McClure
- S&C: Ken Dorsett
- Surface Preparation: Keith Jordan
- Splitflow Support: Neal Domel, Steve Karman, Brian Smith
- LMTAS Program Manager: Jim Robarge
- NASA Program Manager: Farhad Gaffari

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The remainder of the presentation consists of support slides.

The MTVI model was run in an alpha sweep at zero sideslip and small (2 degrees) sideslip.

Configuration (MTVI)



MTVI, α -Sweep, Inviscid									
β	α								
0		12		20		30		40	
2	6	12	16	20	25	30	35	40	45

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The ICE model was run for an alpha sweep at several sideslip angles (0,5,10,20 degrees). A beta-sweep was also done at 20 degrees AOA.

Configuration (Tailless Delta) Inviscid



Tailless Delta, α -Sweep, Inviscid										
β	α									
0	0		10	15	20					30
5	0		10	15	20					30
10	0	5	10	15	20	22	24	26	28	30
20	0	5	10	15	20	22	24	26	28	30

Tailless Delta, β -Sweep, Inviscid									
α	β								
20	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	

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A few viscous cases were also added to investigate the region near $\text{AOA}=24$ at sideslip, an area where the results compared poorly.

Configuration (Tailless Delta) Viscous



Tailless Delta, Viscous			
β	α		
10	22	24	28
20	22		28

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Results



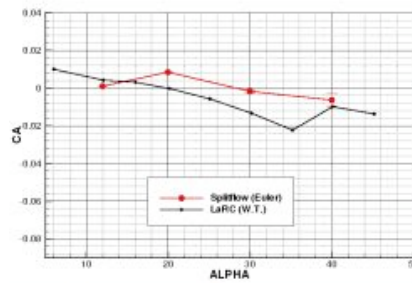
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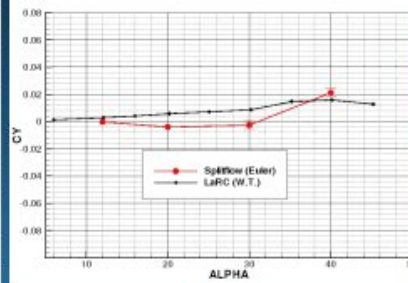
MTVI $\beta = 0^\circ$



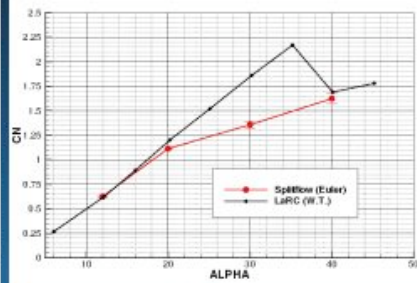
• C_A



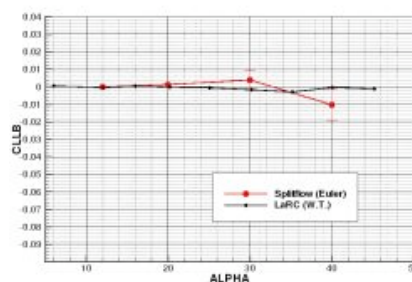
C_Y



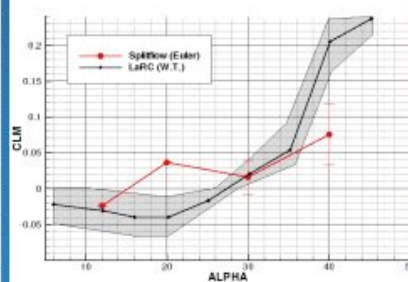
C_N



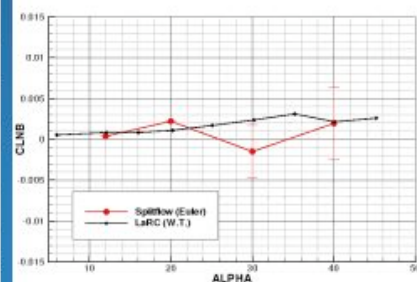
• C_l



C_m



C_n

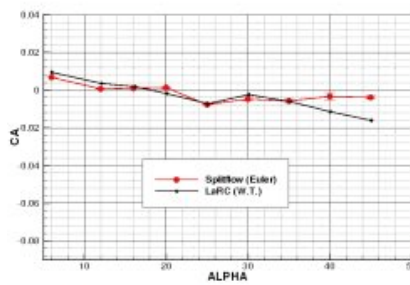


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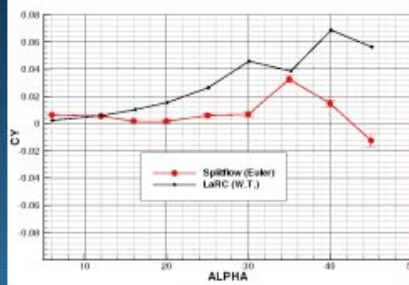
MTVI $\beta = 2^\circ$



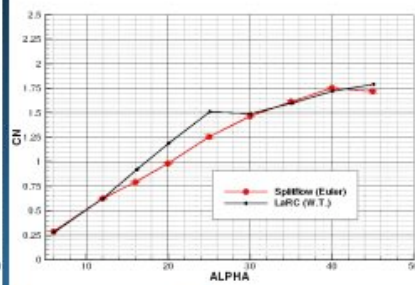
• C_A



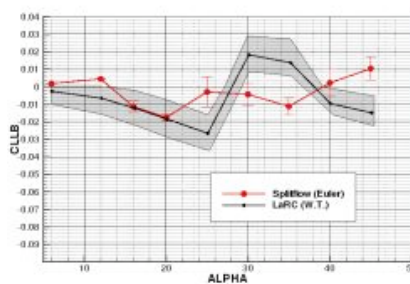
C_Y



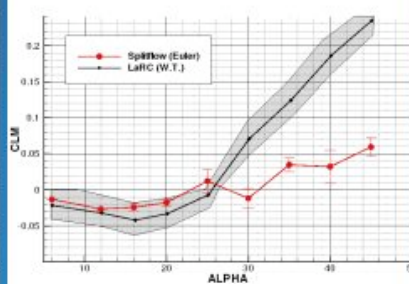
C_N



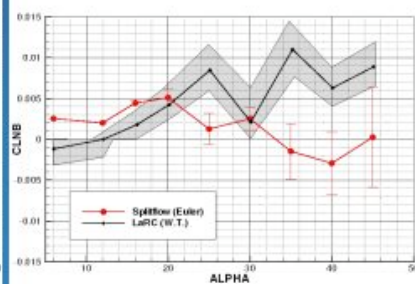
• C_l



C_m



C_n

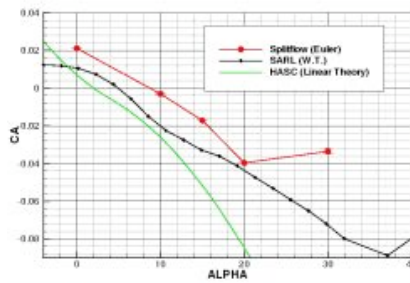


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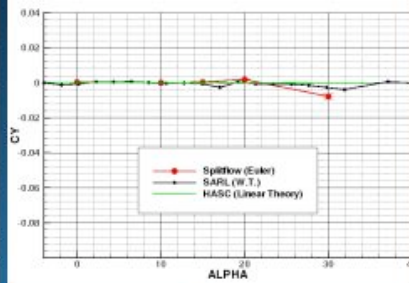
Tailless Delta (ICE) $\beta = 0^\circ$



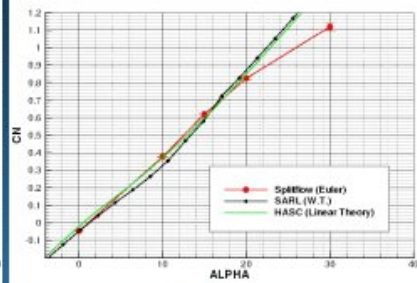
• C_A



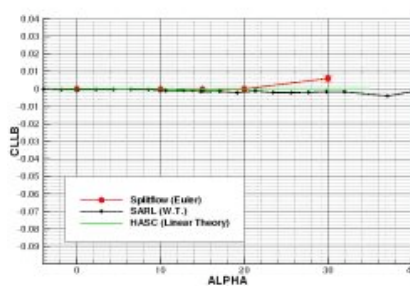
C_Y



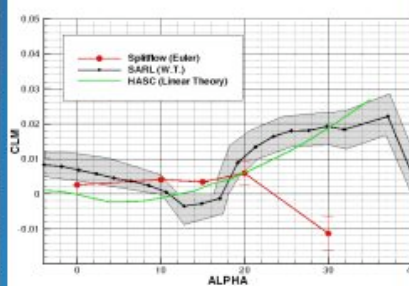
C_N



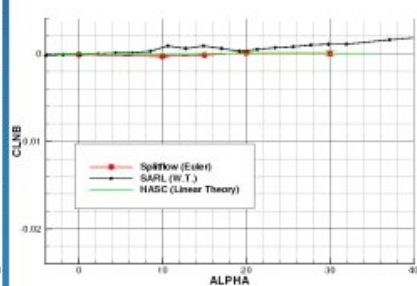
• C_l



C_m



C_n

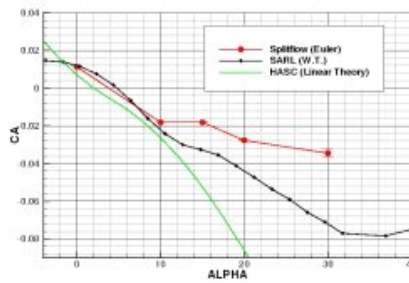


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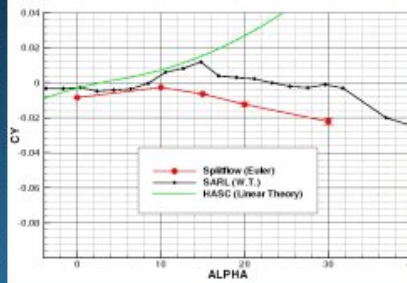
Tailless Delta (ICE) $\beta = 5^\circ$



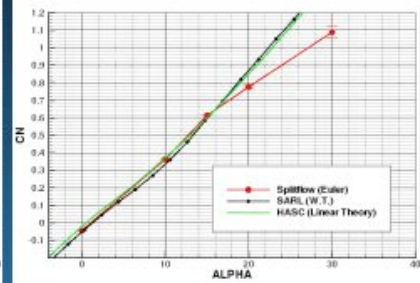
• C_A



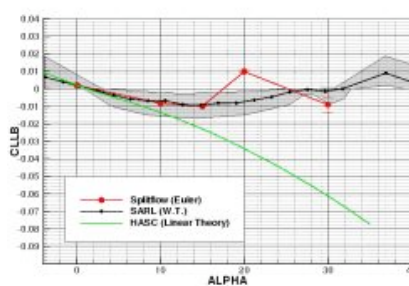
C_Y



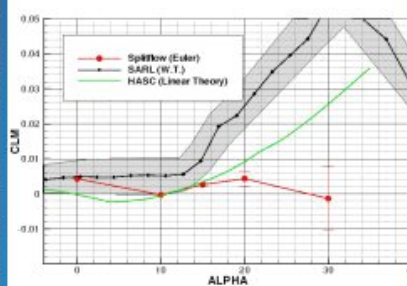
C_N



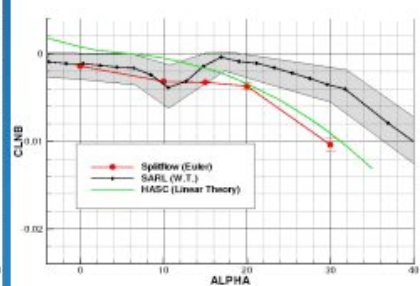
• C_l



C_m



C_n

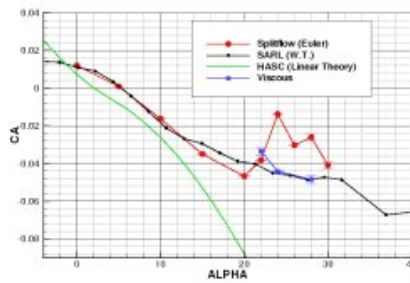


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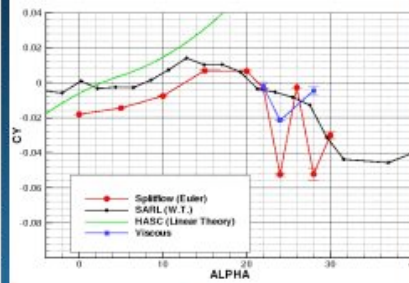
Tailless Delta (ICE) $\beta = 10^\circ$



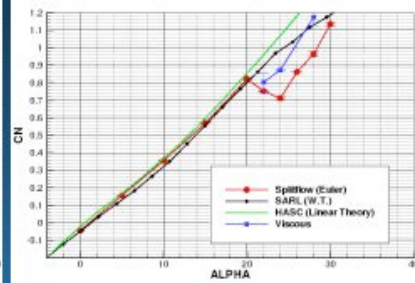
• C_A



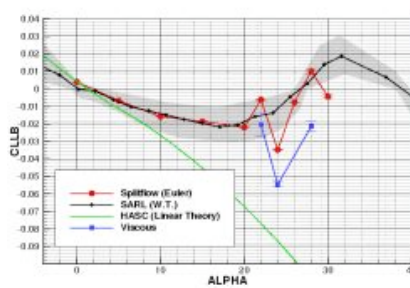
C_Y



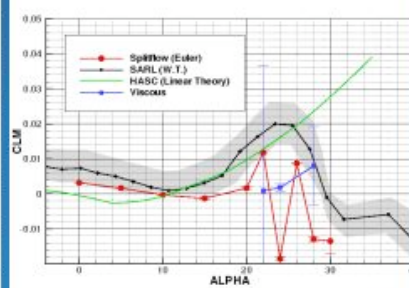
C_N



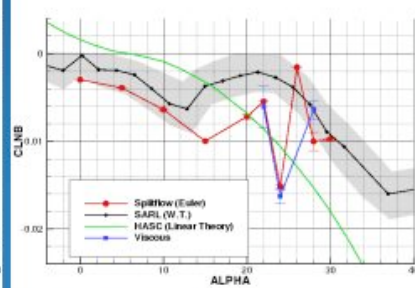
• C_l



C_m



C_n

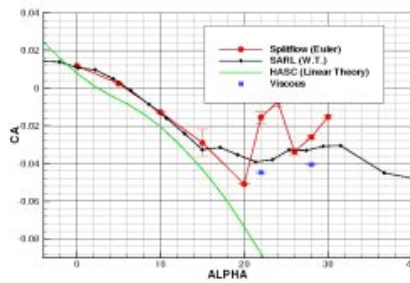


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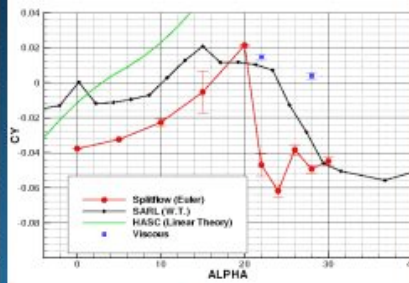
Tailless Delta (ICE) $\beta = 20^\circ$



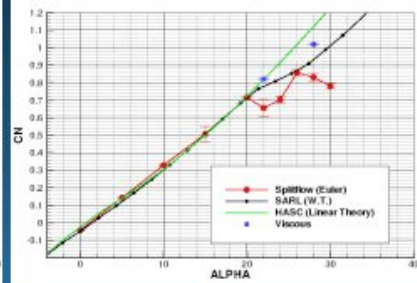
• C_A



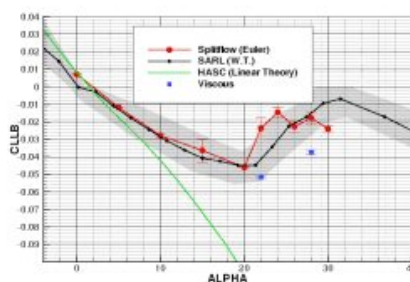
C_Y



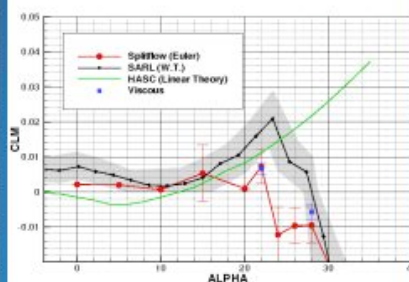
C_N



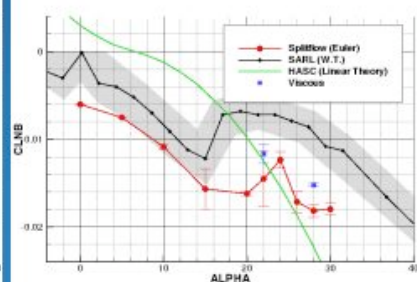
• C_l



C_m



C_n

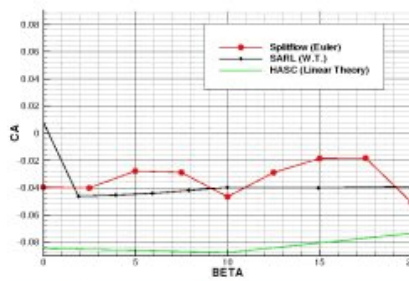


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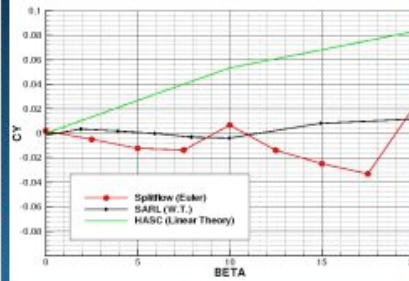
Tailless Delta β -sweep



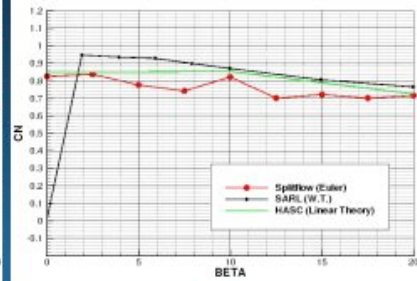
• C_A



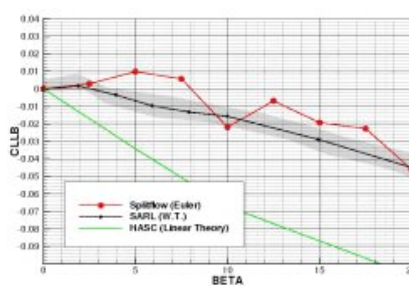
C_Y



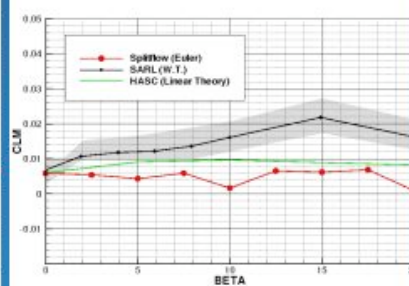
C_N



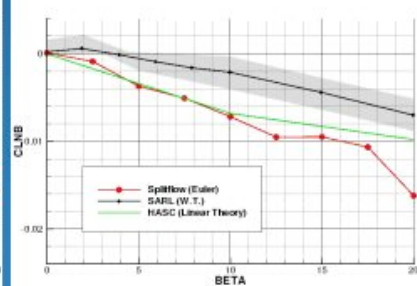
• C_l



C_m



C_n



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Most of this is old news. Our J90 isn't even used to heat the room anymore. These cases would require about 4 hours on 16 CPU of our Pentium4 cluster, which is very inexpensive.

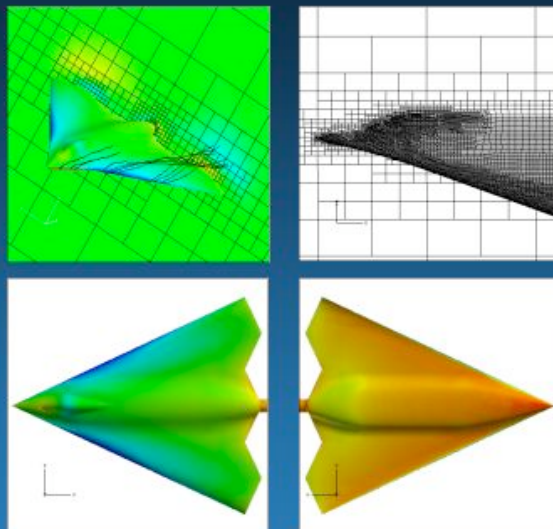
CPU Requirements



- Cray C90 Hours Numbers Were Suspicious.
 - Suspect Trouble in the Accounting System.
- Wall Clock (Real Computing Environment)
 - Approximately 40~130 Hours Runtime in Our Environment
 - (Heavily-Loaded J90, 4~8 Processors on a Parallel Run, Closer to One or Two Weeks Including Queue Waits)
- Affected by
 - Refining Often?
 - Multiple Checkpoint-File Writes, Etc.

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Future Efforts in Grid Generation



Research work on Splitflow is progressing to build grids that are more acceptable for viscous simulation.

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5 years ago, this is how this project concluded—we needed faster solutions and more of them. Minimum drag, of course, is now the subject of its own AIAA committee and annual meetings, and it doesn't seem that anyone has a good handle on it yet.

What is really needed?



- Reduced Turnaround Time
 - Smoother Grids?
 - Multigrid?
 - Massively Parallel?
- C_L , C_M
 - Manageable With Proper Technique and Sufficient Patience and Proper Physical Models.
- C_{D0}
 - Statistical Formulation?
 - Laminar NS? RANS? LES? DNS?

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