Applied Aerodynamics Technical Committee

6th CFD Drag Prediction Workshop
Washington D.C. – June 2016

DPW 6 Summary of Participant Data
CRM Cases 2-5

Ed Tinoco,

Olaf Brodersen,

and the DPW Organizing Committee

Outline:

- Participant Data
- Case 2: CRM Nacelle-Pylon Drag Increment
- Case 3: CRM WB Static Aero-Elastic Effect
- Case 4: CRM WB Grid Adaptation
- Case 5: CRM WB Coupled Aero-Structural Simulation
- Separation
- Observations/Issues

Participant Data:

- **48 Total Data Submittals**
- **25 Teams/Organizations**
  - 12 N. America, 6 Europe, 6 Asia, 1 S. America
  - 8 Government, 5 Industry, 7 Academia, 5 Commercial
  - 2 for Case 5 only
- **Grid Types:**
  - 17 Common Unstructured (12 teams)
  - 15 Custom Unstructured (11 teams)
  - 6 Overset (3 Teams)
  - 3 Structured Multi-block (3 Teams)
  - 5 Custom Cartesian (2 Teams)
- **Turbulence Models:**
  - 36 SA (all types), 6 SST, 2 k-kLe, 2 k-e Lam, 1 EARSM, 1 LBM-VLES, 1 RSM-ω

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CRM Cases 2-5 Participants

Team	ID	SYM	Name	Organization	Code	Grid	Turbulence Model
1	A1	A	Tony Sclafani	Boeing, BCA Advanced Concepts, Long Beach CA	Overflow v2.2k	Overset	SA-RC
	A2	a			Overflow v2.2k	Overset	SA-RC w/QCR on
2	B1	B	Khaled Abdol-Hamid	NASA Langley Research Center	FUN3D 12.8	Unst-Geolab	k-kL-MEAH2015 w/Limiter
	B2	b			FUN3D 12.8	Unst-Geolab	k-kL-MEAH2015 no-limiter
	B3	α			FUN3D 12.8	Unst-Geolab	SA no-limiter
3	C1	C	Brennan Blumenthal	NASA Langley Research Center	USM3D	Unst-Geolab	SA
4	D1	D	Jiangtao Chen	CARDC	Mflow	Unst-custom	SA
	D2	d			Mflow	Unst-custom	SA
	T1	T	Yuntao Wang		TRIP	CommonMB	SST-2003
5	E1	E	Atsushi Hashimoto	JAXA	FaSTAR	Unst-Geolab	SA-noft2-R w/QCR2000
6	F1	F	Krishna Zore	Ansys	Fluent		
7	G1	G	Benedikt König	EXA Powerflow	PowerFLOW	Custom Cart	LBM-VLES
8	H1	H	Ales Prachar/Peter Eliasson	VZLU/FOI	Edge	Unst-Geolab	SA
	H2	h			Edge	Unst-Geolab	EARSM
9	I1	I	Anna Rubekinak	Mentor Graphics	FloEFD	Custom Cart	k-e Lam-Bremhorst
	I2	β			FloEFD	Custom Cart	k-e Lam-Bremhorst
10	J1	J	Brian Edge	Metacomp	CFD++	Unst-Boeing	SA
	J2	ϑ			CFD++	Unst-Boeing	SST
	J3	φ			CFD++	Unst-Geolab	SA
	J4	Ω			CFD++	Unst-custom	Realizable k-epsilon
11	K1	K	Taku Nagata	Kawasaki Heavy Industries	Cflow	Unst-Boeing	SA-noft2
	K2	k			Cflow	Unst-Boeing	SA-noft2 w/QCR200
	K3	γ			Cflow	Custom Cart	SA-noft2
	K4	Γ			Cflow	Custom Cart	SA-noft2 w/QCR200
12	L1	L	Stefan Keye / Vamshi Togiti	DLR	TAU	Unst-Custom	RSM-ω
	L2	σ			TAU	Unst-Custom	SA-neg
13	M1	M	Ryan S. Glasby	Tennessee, Pointwise, NASA Langley	COFFE/KCFD	Unst-custom	SA-neg
	M2	m			COFFE/KCFD	Unst-custom	SA-neg w/QCR2000
14	N1	N	N. Balakrishnan	Indian Institute of Science	HiFun	Unst-custom	SA

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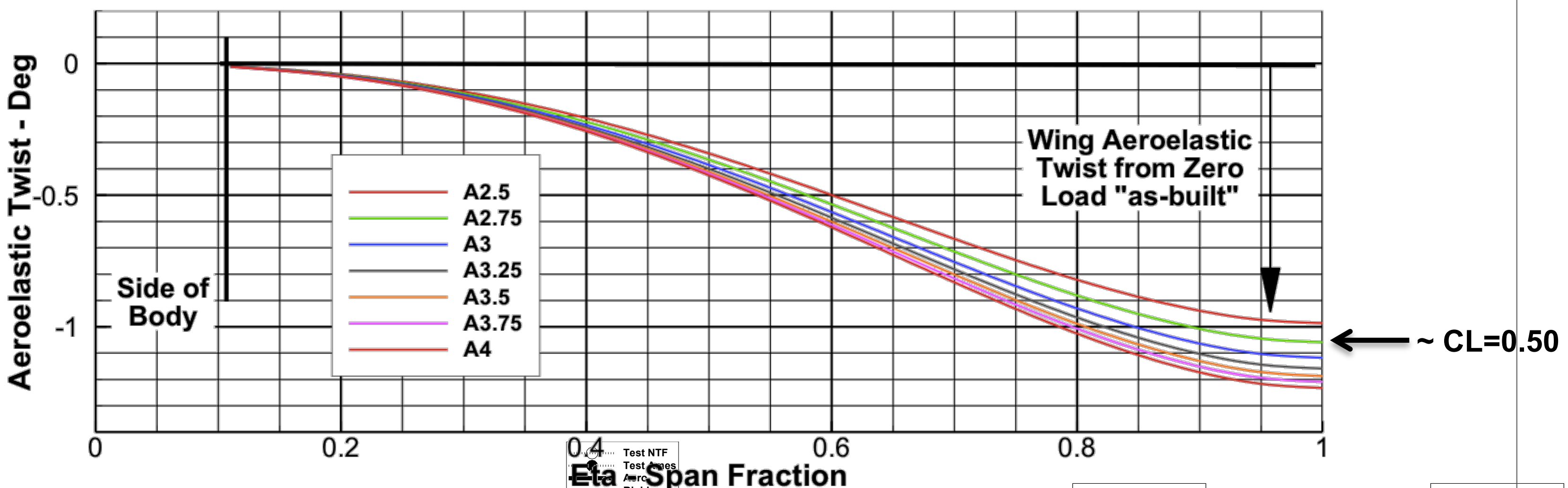
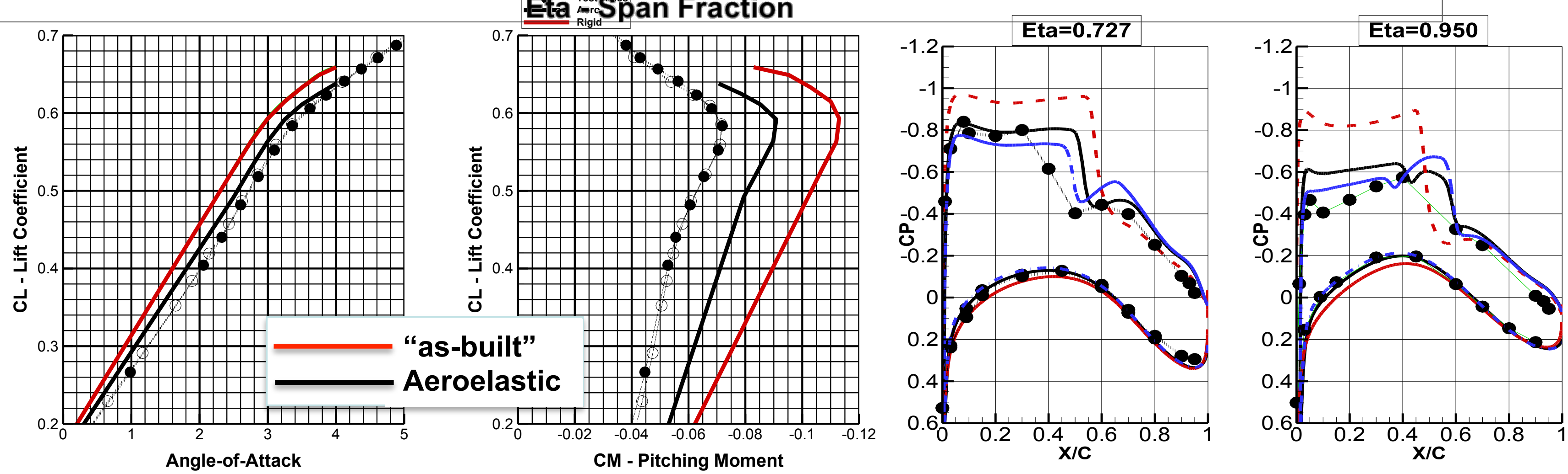
CRM Cases 2-5 Participants							
Team	ID	SYM	Name	Organization	Code	Grid	Turbulence Model
15	O1	O	David Hue	ONERA	elsA	Overset	SA
	O2	ϕ			elsA	Overset	SA-QCR2000
16	P1	P	Todd Michal	Boeing, St. Louis	BCFD	Unst-Boeing	SA-RC
	P2	π			GGNS	All Tets	SA-RC
17	Q1	Q	Gaetan Kenway	MDOlab, University of Michigan	SUMad	Embraer MB	SA 1stOrder
	Q2	q			SUMad	Unst-custom	SA
18	R1	R	Andrei Cimpoeru	CFMS, Zenotech, ARA	ZCFD		
19	S1	S	Kelly Laflin	Textron Aviation (Cessna), FUN3D	FUN3D	Unst-Geolab	SA-RC
20	U1	U	Jim Coder	Applied Research Lab, Penn State	Overflow 2.21 3rd Order WENO	Overset	SA-RC W/QCF2000
	U2	u			Overflow 2.21 5TH Order WENO	Overset	SA-RC W/QCF2000
21	V1	V	Rodrigo Felix de Souza	Embraer S/A	CFD++	Unst-Geolab	SST
	V2	ς			CFD++	Embraer MB	SST
	V3	Ξ			CFD++	Unst-custom-A	SST
	V4	Ψ			CFD++	Unst-custom-I	SST
22	W1	W	Dominic Chandar	Institute of High Performance	µSICS		
23	X1	X	Patrick Hanley	Hanley Innovations	Stallion3D		
24	Y1	Y	Neil Ashton	University of Oxford, ESI Group, BETA CAE Systems	OpenFOAM		
25	Z1	Z	Yasushi Ito	JAXA	TAS limiter K=1	Unst-Geolab	SA-noft2-R w/QCR2000
	Z2	ζ			TAS limiter K=5	Unst-Geolab	SA-noft2-R w/QCR2000
	Z3	Δ			TAS limiter K=10	Unst-Geolab	SA-noft2-R w/QCR2000

CRM geometry for DPW6 includes the static aeroelastic twist and deformation experienced by the model at different angles of attack





Should We Compare to Wind Tunnel?

Wind Tunnel	CFD
Walls	Free Air
Support System (Sting)	Free Air
Laminar/Turbulent (Tripped)	“Fully” Turbulent (usually)
Aeroelastic Deformation	Static Measured Deflections
Measurement Uncertainty	Numerical Uncertainty & Error
Corrections for known effects	No Corrections

- Wind Tunnel and CFD measure/compute different things!
- Data are included for reference only!

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Case 2: Nacelle-Pylon Drag Increment

- Grid Convergence Study
- NASA Common Research Model, Wing-Body and Wing-Body-Nacelle Pylon
- Mach=0.85, C_L=0.500±0.001
- Chord Reynolds Number: 5×10^6
- Grid Resolution Level:
  - 1) Tiny 2) Coarse 3) Medium,
  - 4) Fine 5) Extra-Fine 6) Super-Fine
- Drag Increment between Wing-Body and Wing-Body-Nacelle-Pylon

Grid Convergence?

Richardson Extrapolation:

- Standard 2nd order least squares fit
- For 2nd order codes, should be linear vs.
  $\text{Grid\_Factor} = N^{-2/3}$
- Y-intercept estimates theoretical infinite resolution (continuum) result

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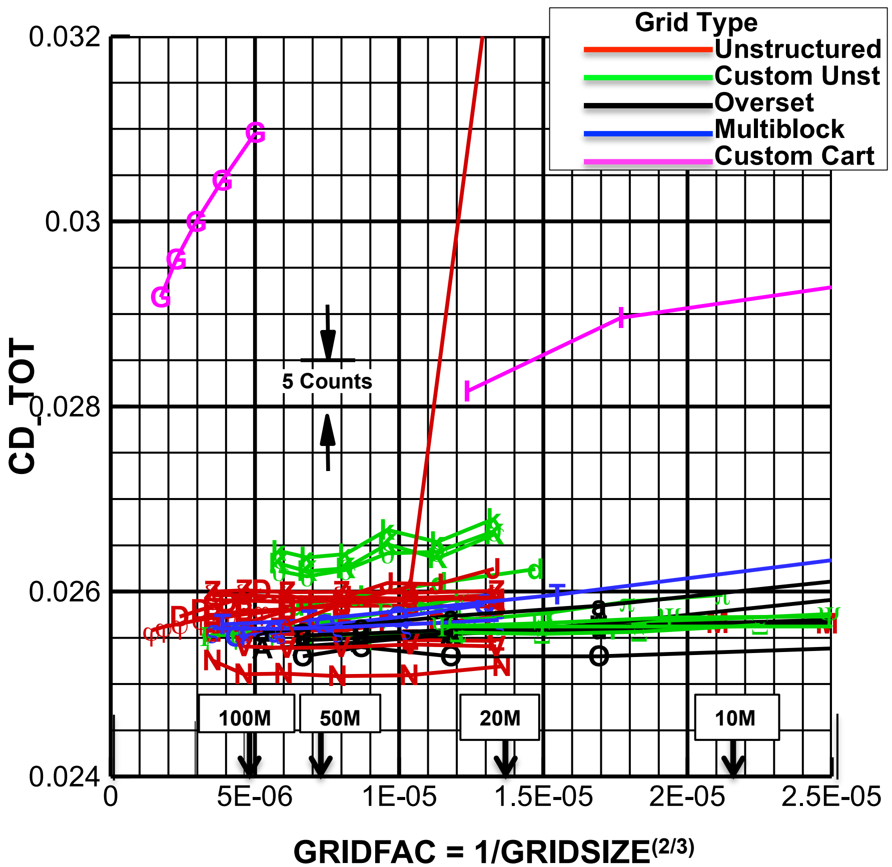
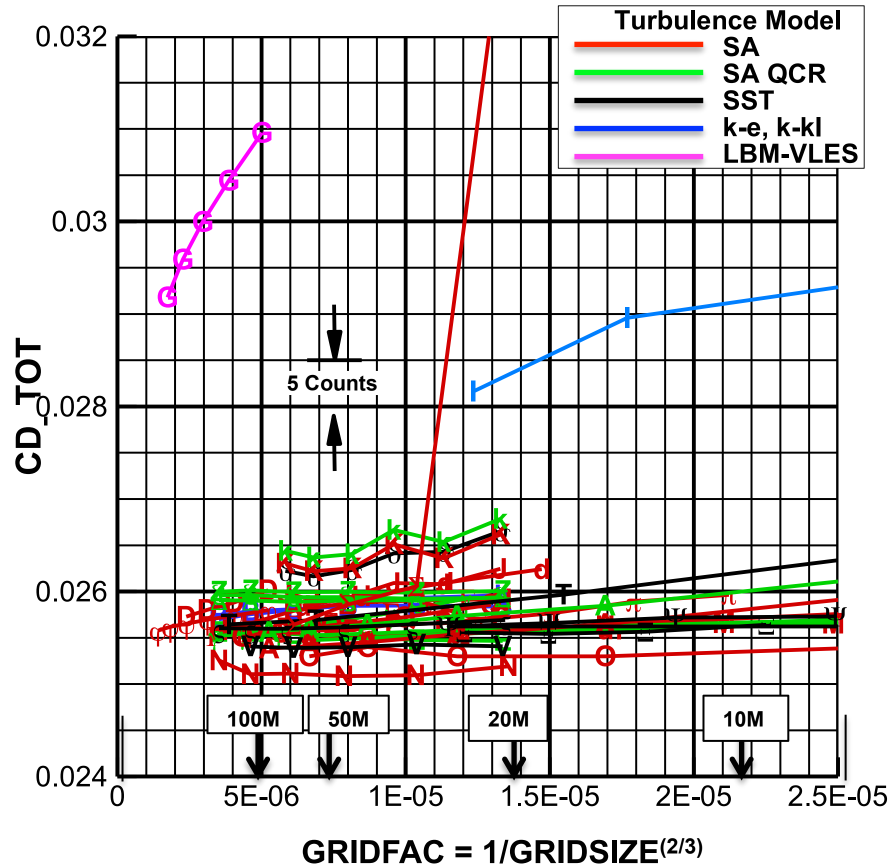
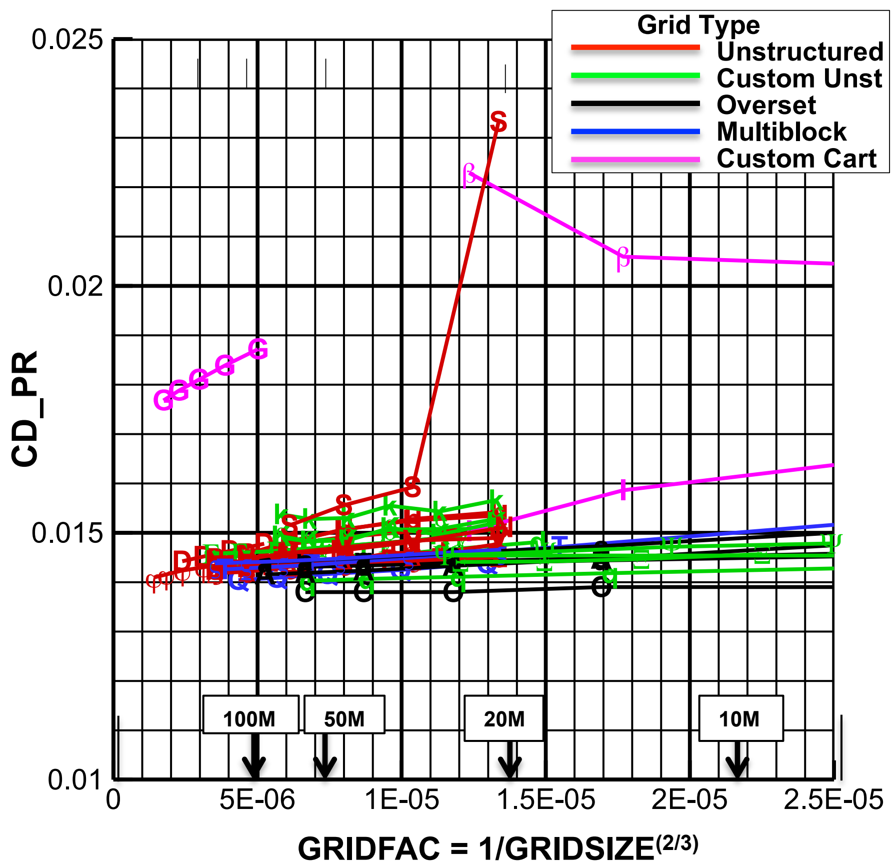
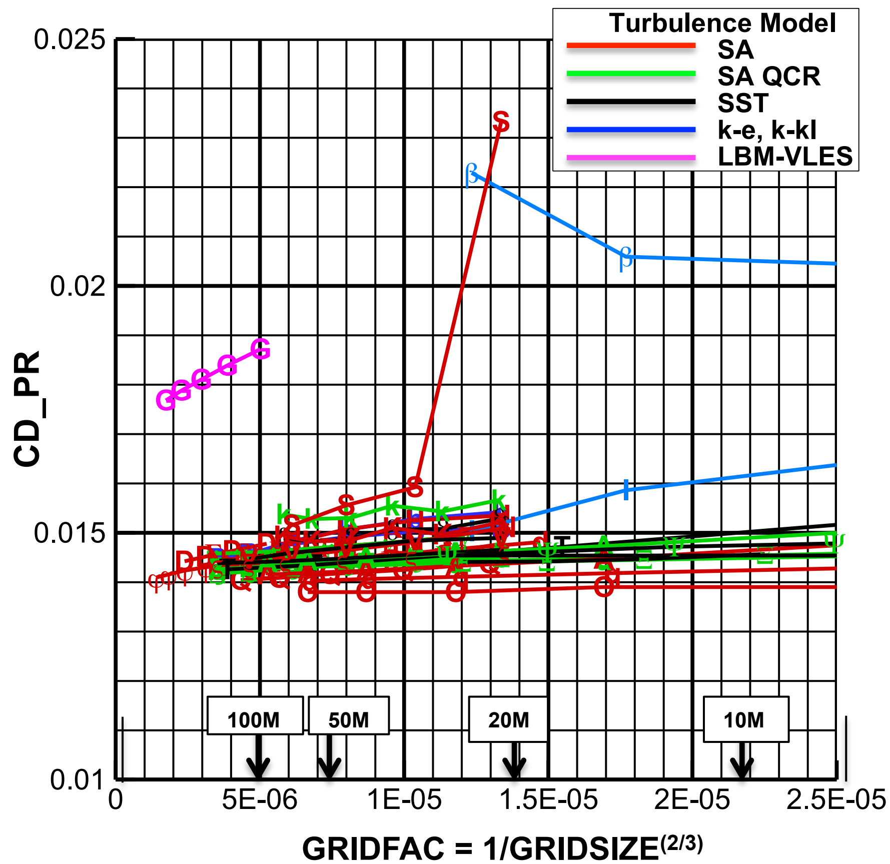
Case 2: CD_TOT - Wing-Body
All Solutions by Grid Type and Turbulence Model



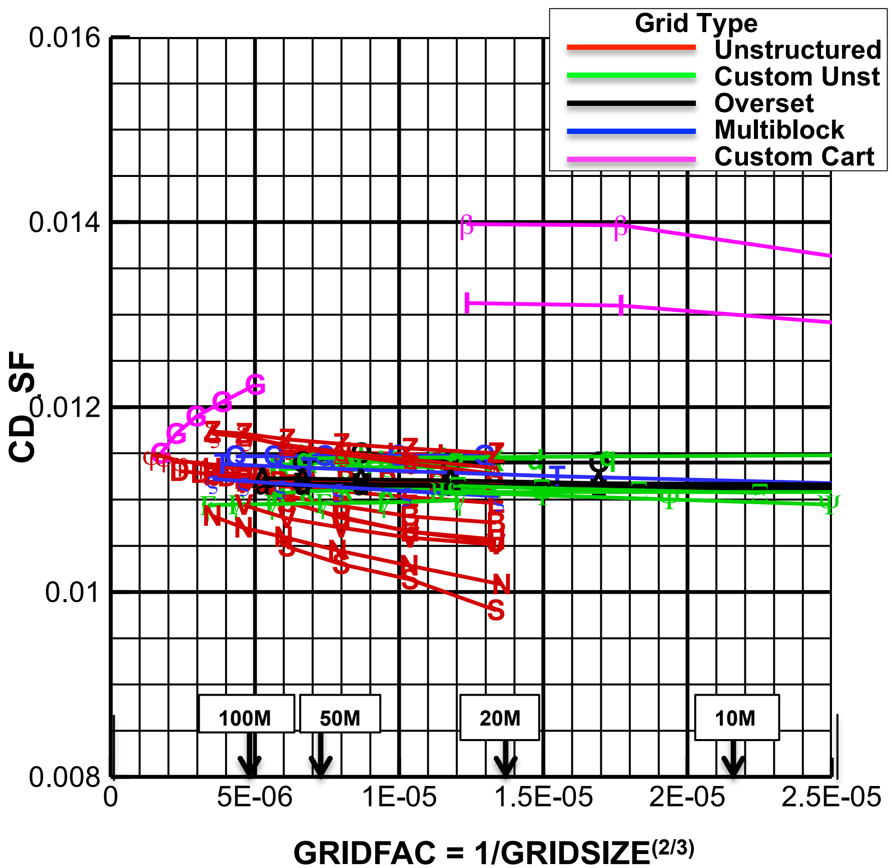


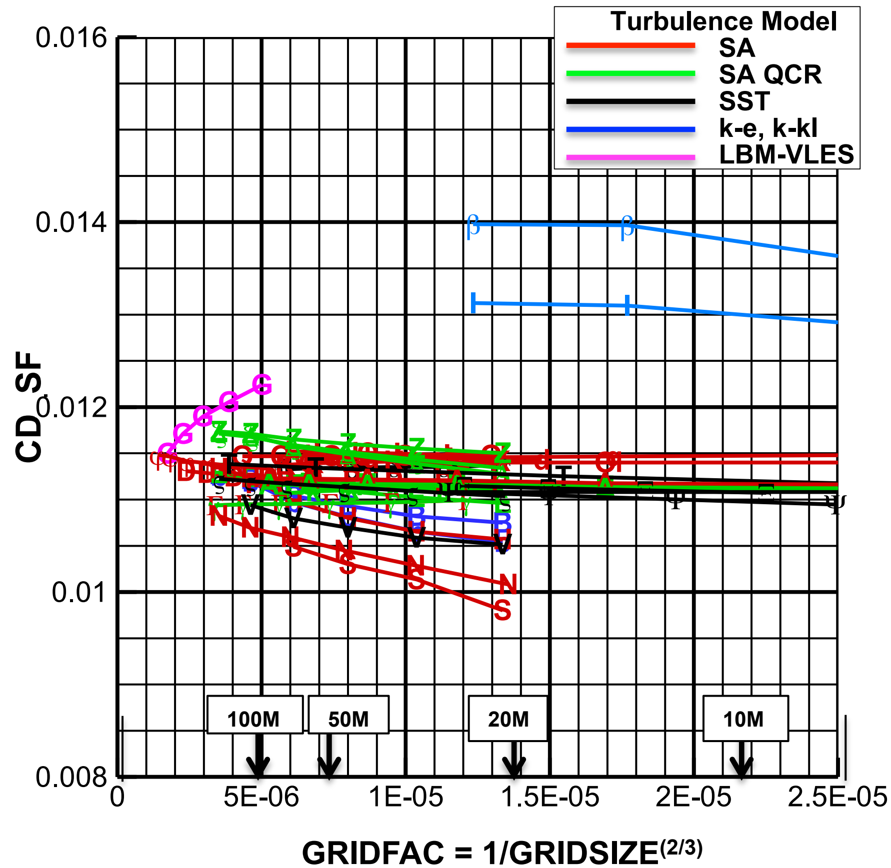
Case 2: CD_PR - Wing-Body
Pressure Drag
All Solutions by Grid Type and Turbulence Model





Case 2: CD_SF - Wing-Body
Skin Friction Drag
All Solutions by Grid Type and Turbulence Model





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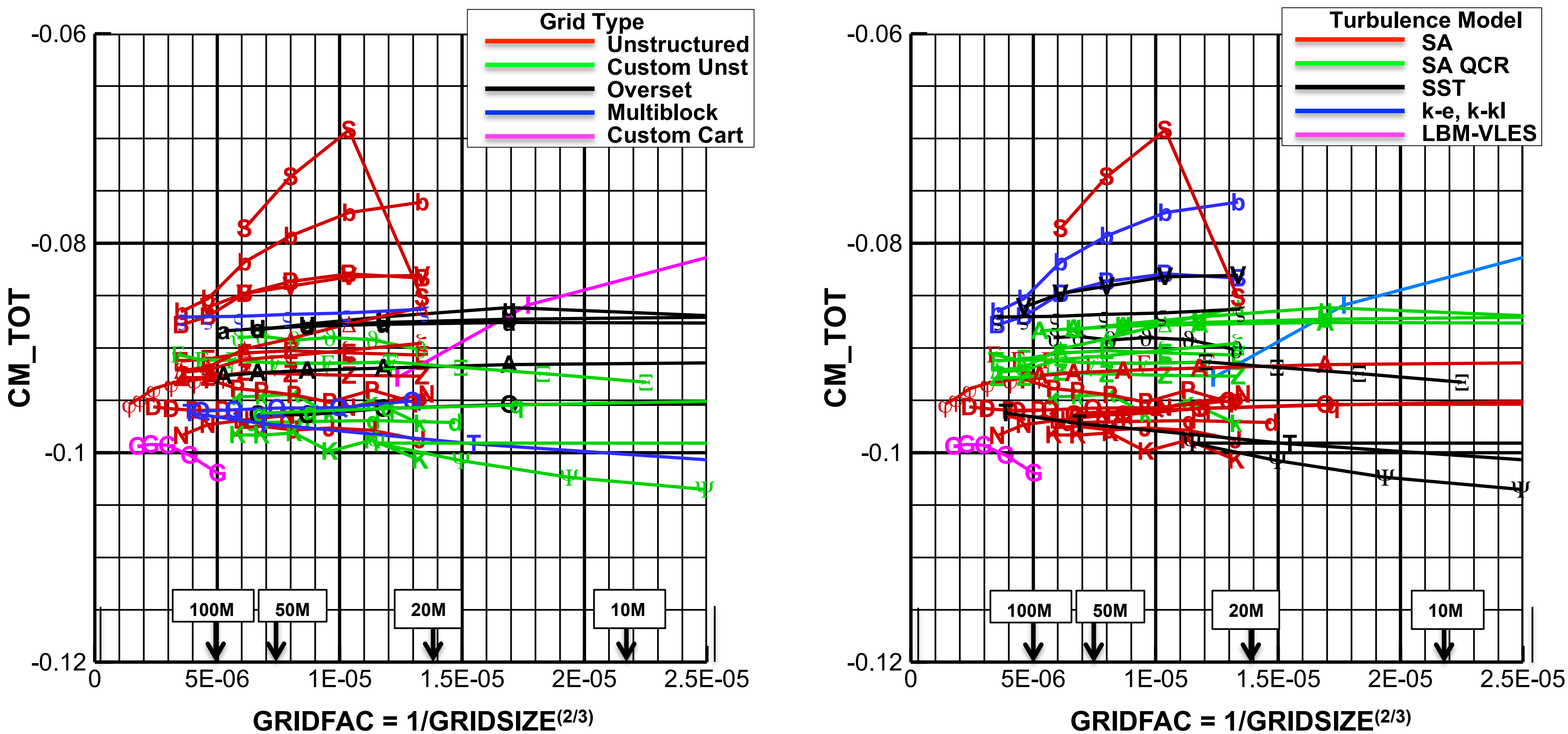
Case 2: CM_TOT - Wing-Body
All Solutions by Grid Type and Turbulence Model



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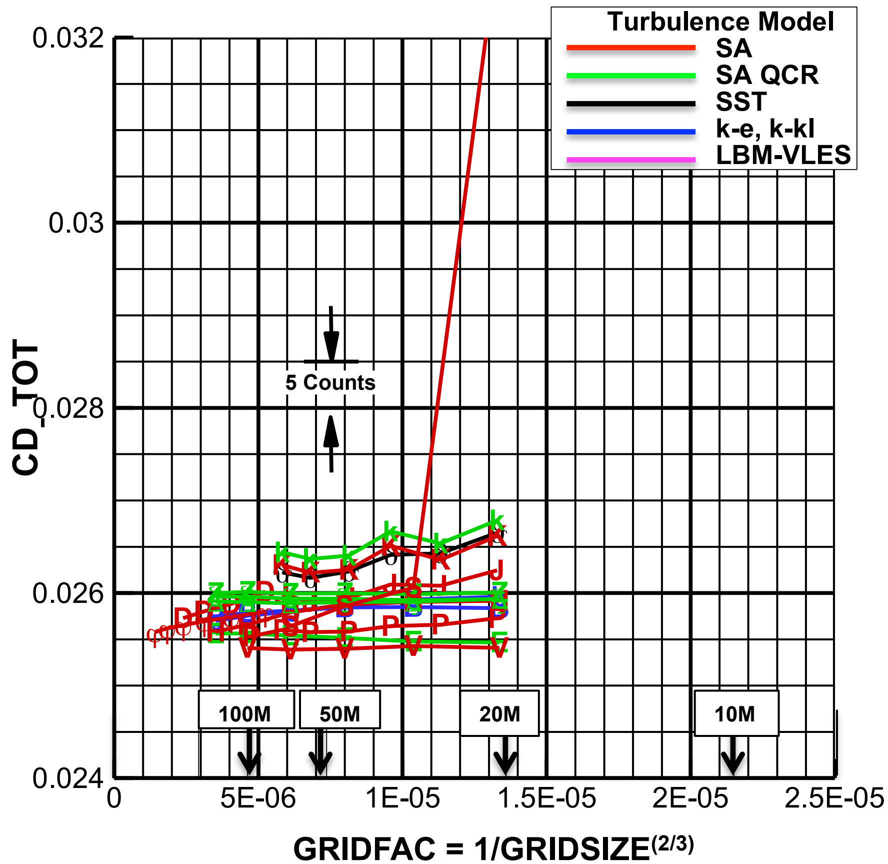
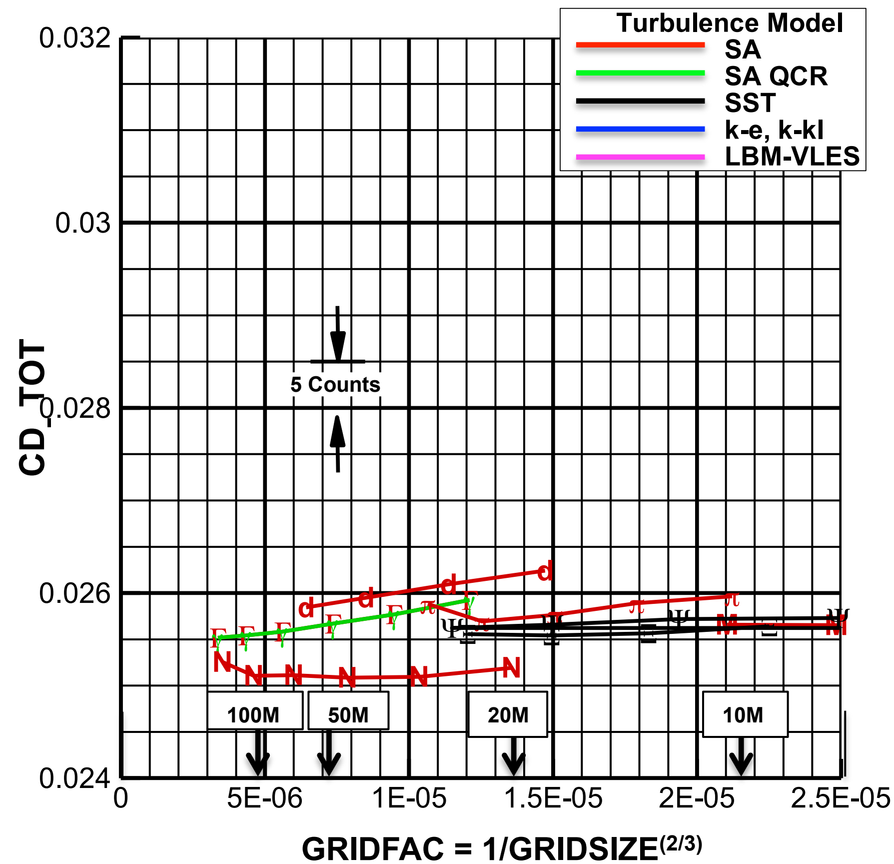
Case 2: CD_TOT - Wing-Body
Solutions by Grid Type and Turbulence Model

Common Unstructured Grids



Custom Unstructured Grids



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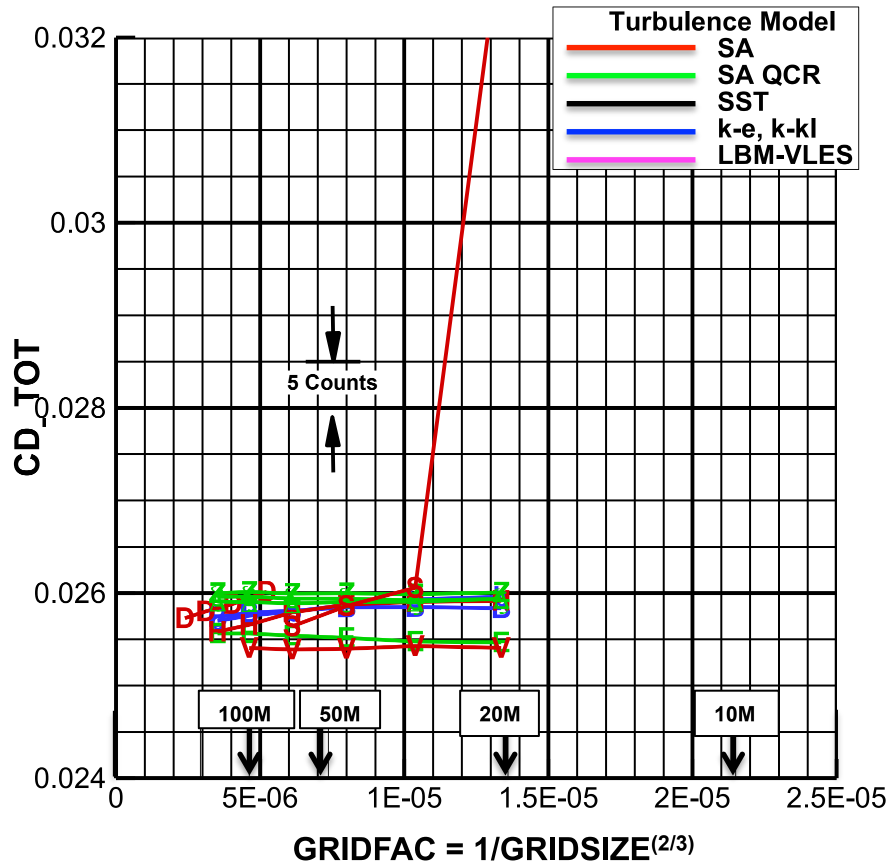
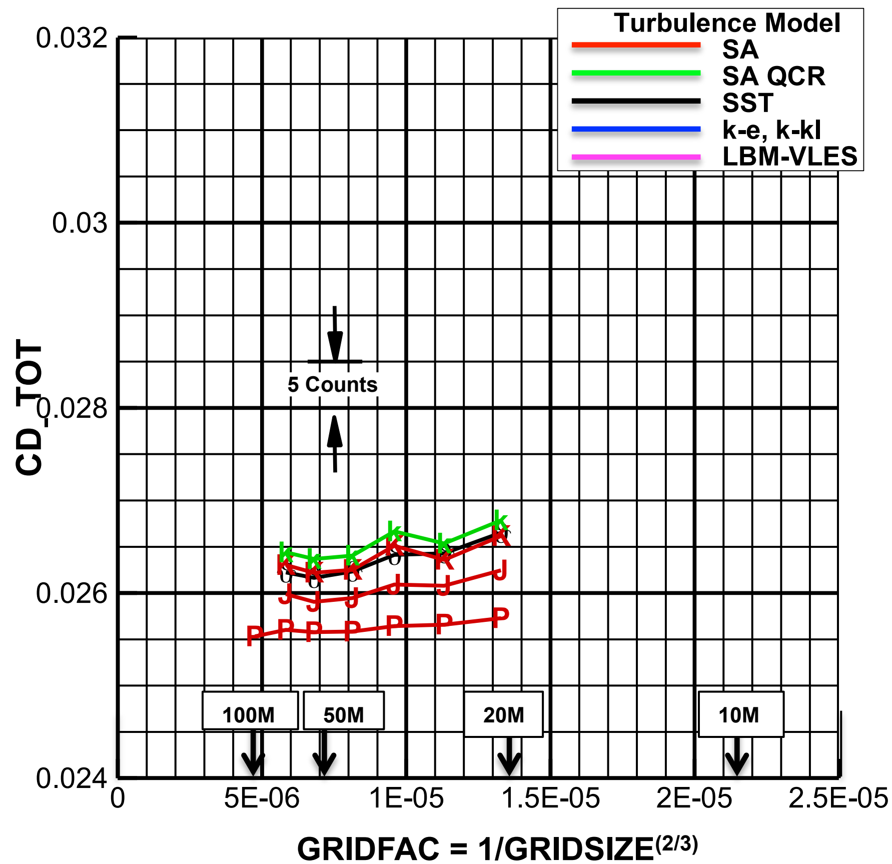
Case 2: CD_TOT - Wing-Body
Solutions by Grid Type and Turbulence Model

Geolab Unstructured Grids



Boeing Unstructured Grids



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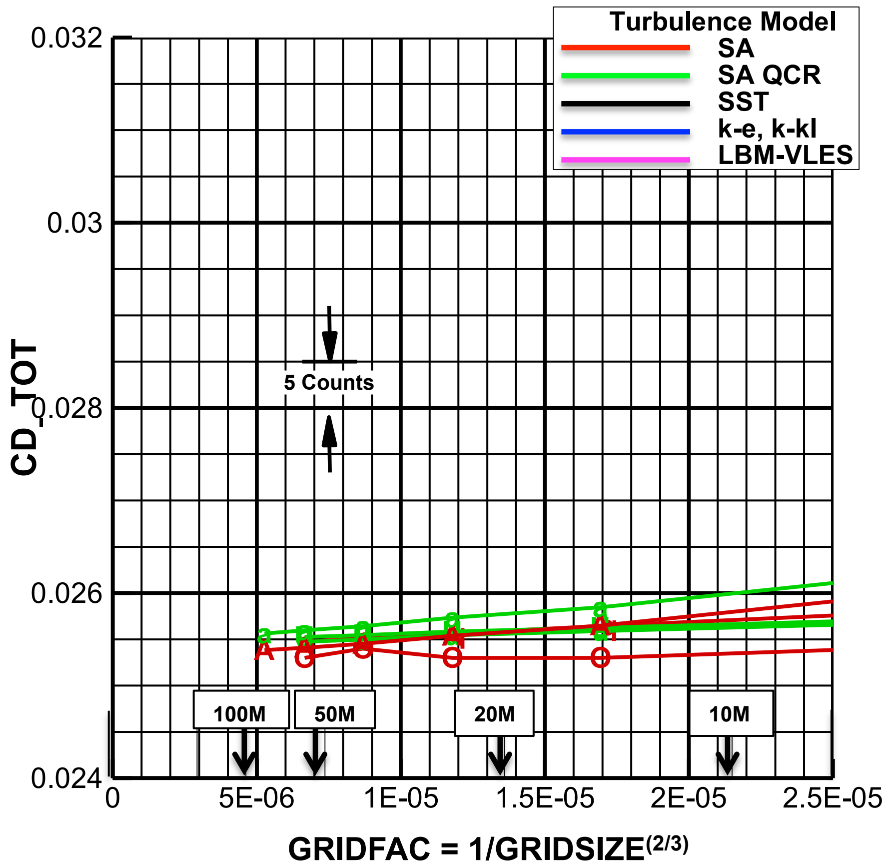
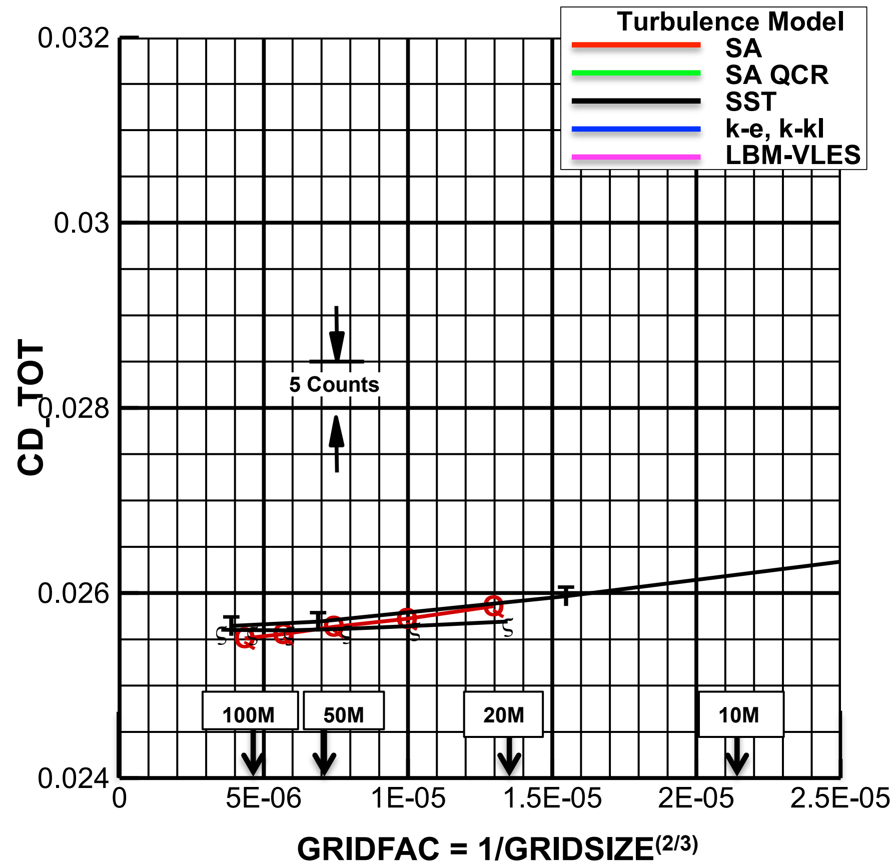
Case 2: CD_TOT - Wing-Body
Solutions by Grid Type and Turbulence Model

Overset Grid



Multiblock Structured Grid



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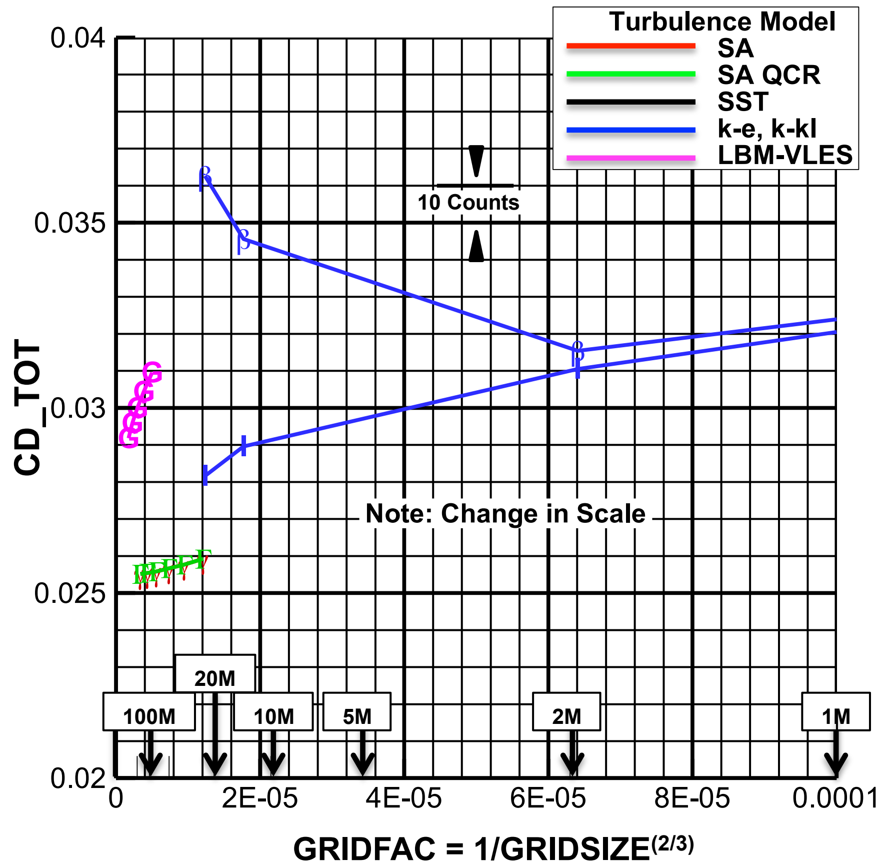
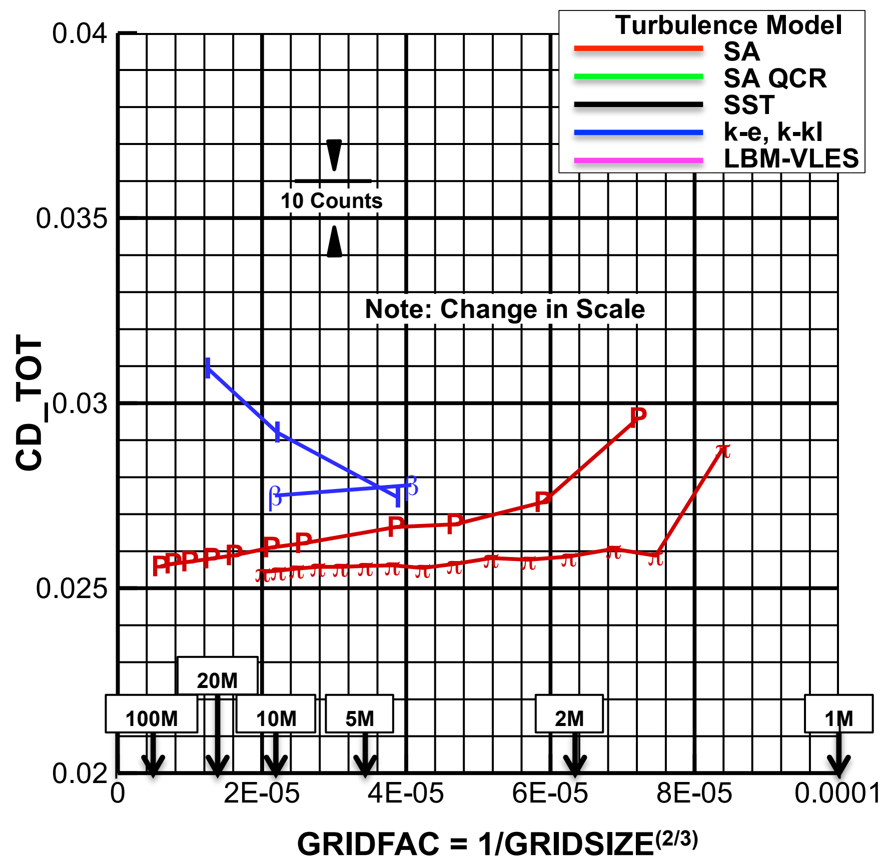
Case 2 & 4: CD_TOT - Wing-Body
Solutions by Grid Type and Turbulence Model

Custom Cartesian Grid



Case 4: Solution Adaptive Grid



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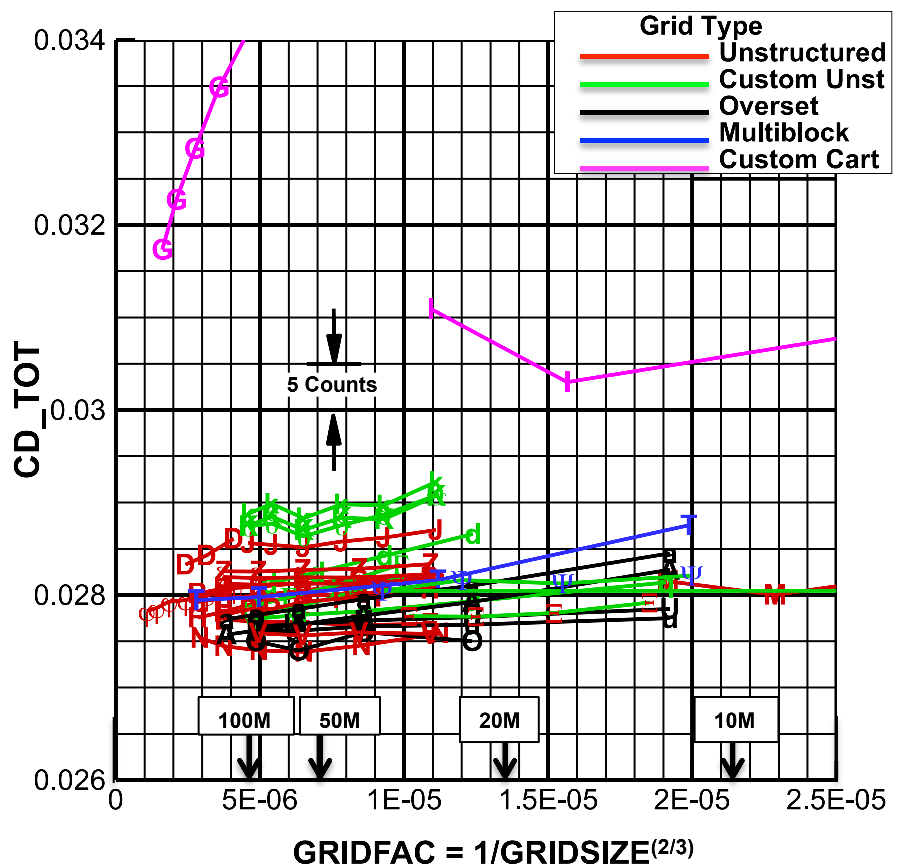
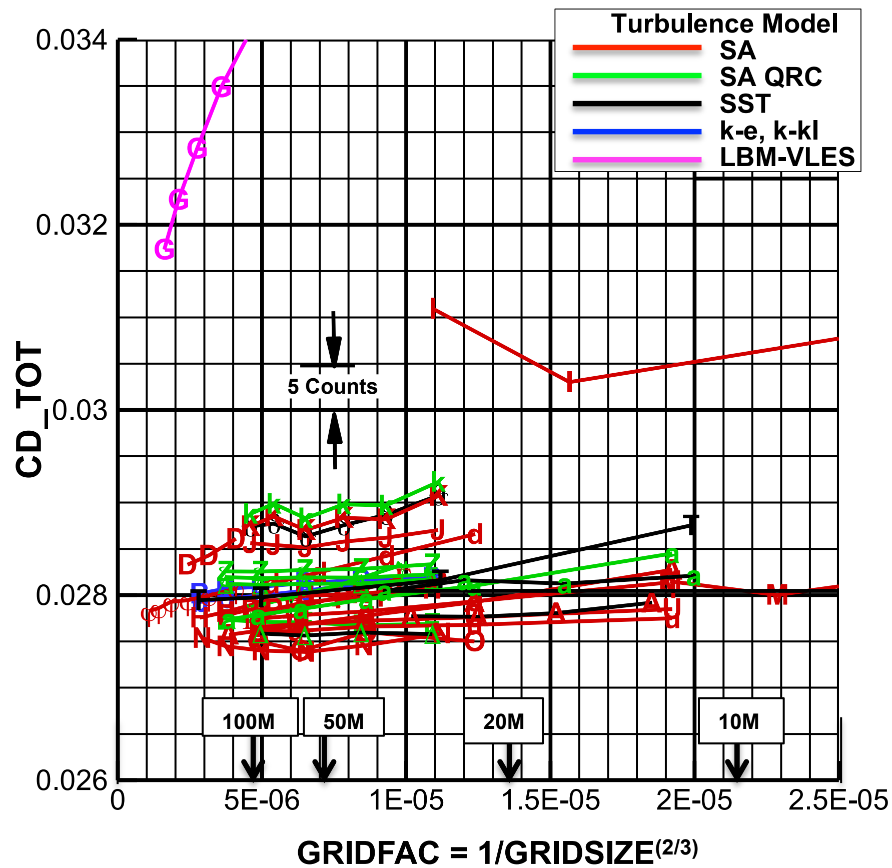
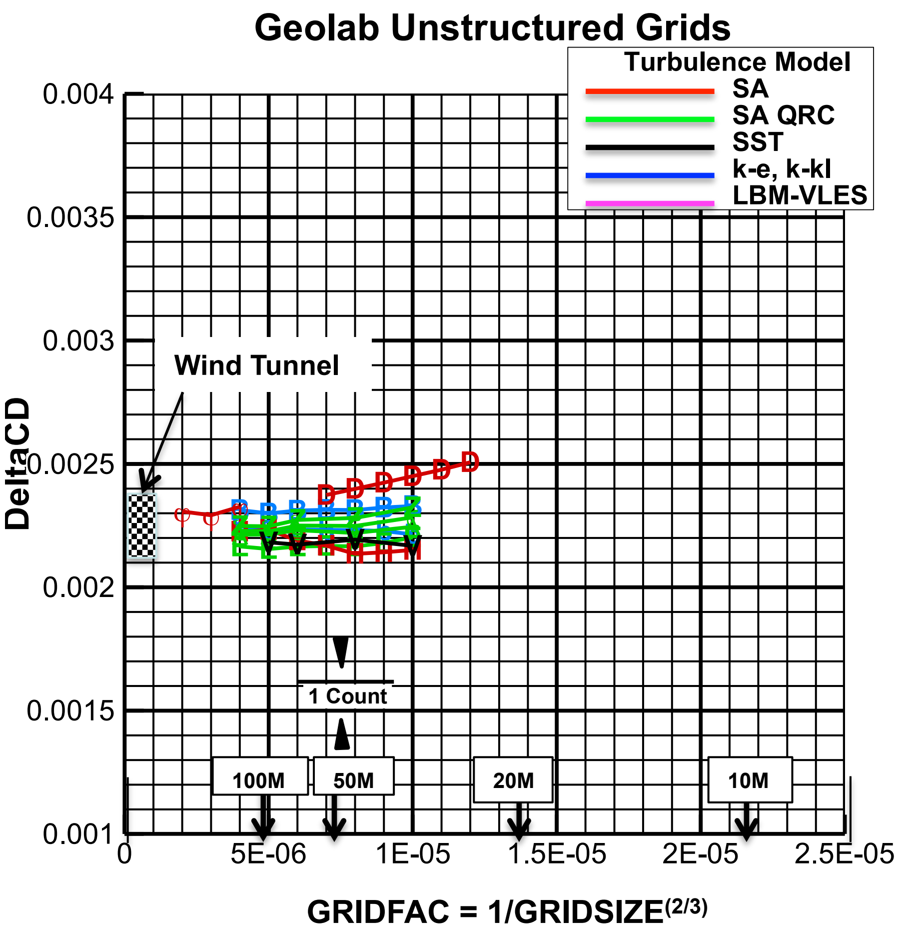
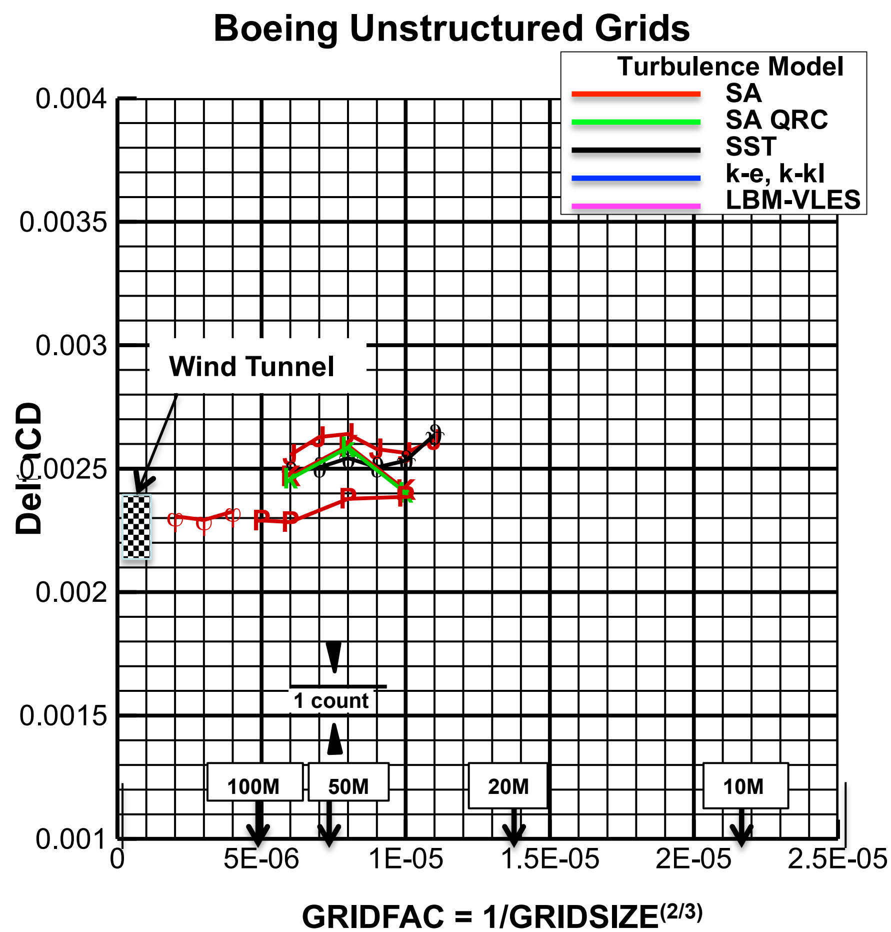
Case 2: CD_TOT - Wing-Body-Nacelle-Pylon
All Solutions by Grid Type and Turbulence Model



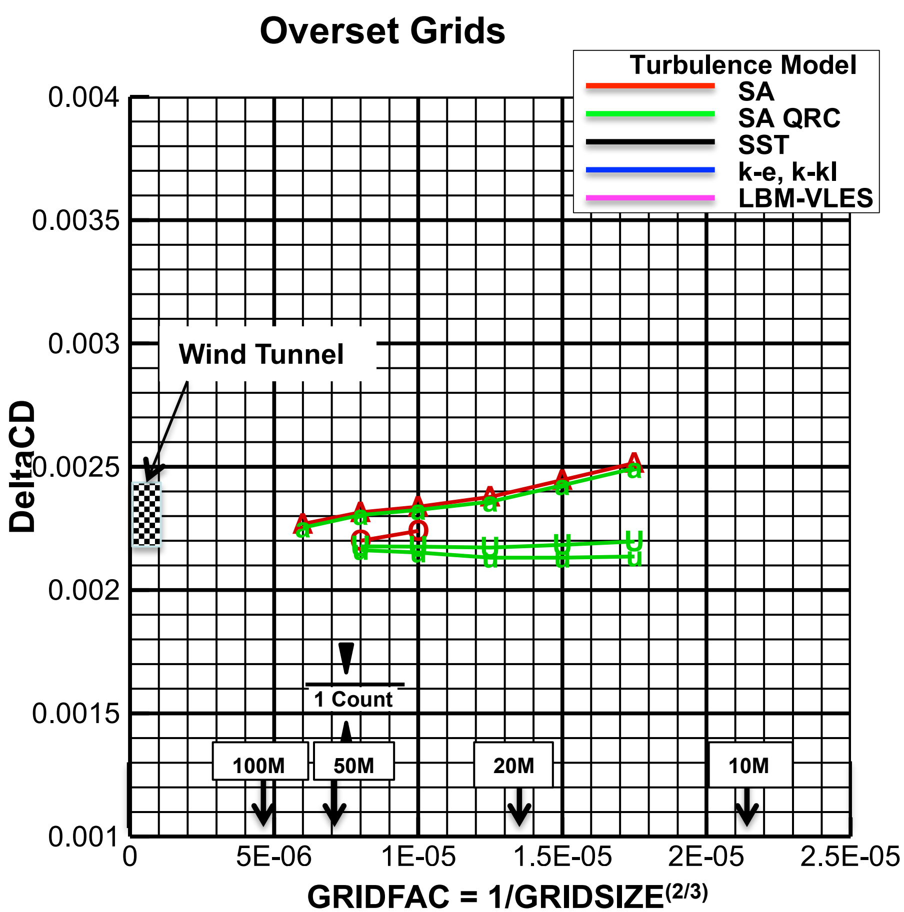


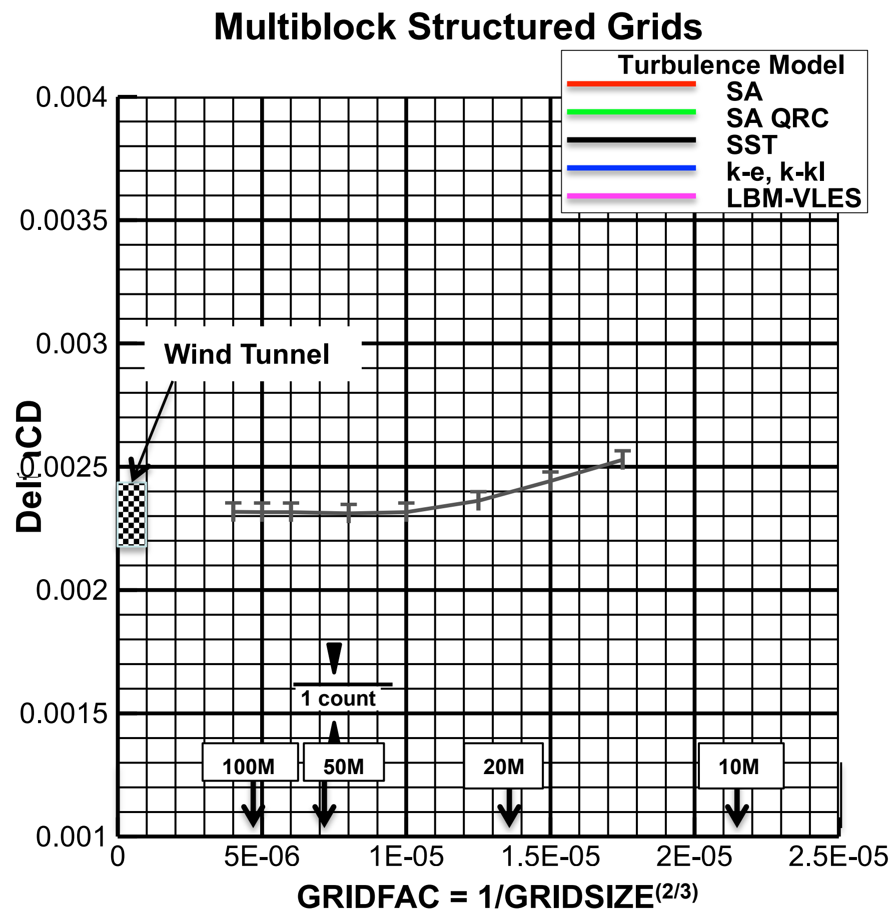
Case 2: CD_TOT - Wing-Body-Nacelle-Pylon minus Wing-Body Solutions by Grid Type and Turbulence Model



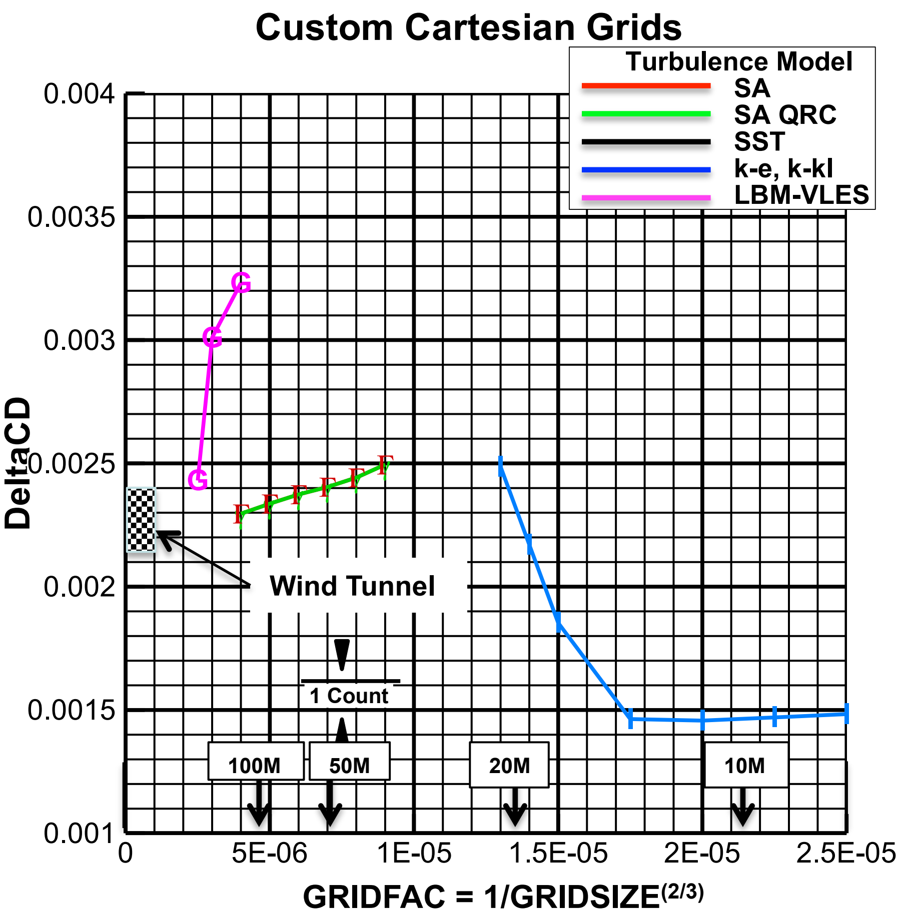


Case 2: CD_TOT - Wing-Body-Nacelle-Pylon minus Wing-Body
Solutions by Grid Type and Turbulence Model





Case 2: CD_TOT - Wing-Body-Nacelle-Pylon minus Wing-Body Solutions by Grid Type and Turbulence Model



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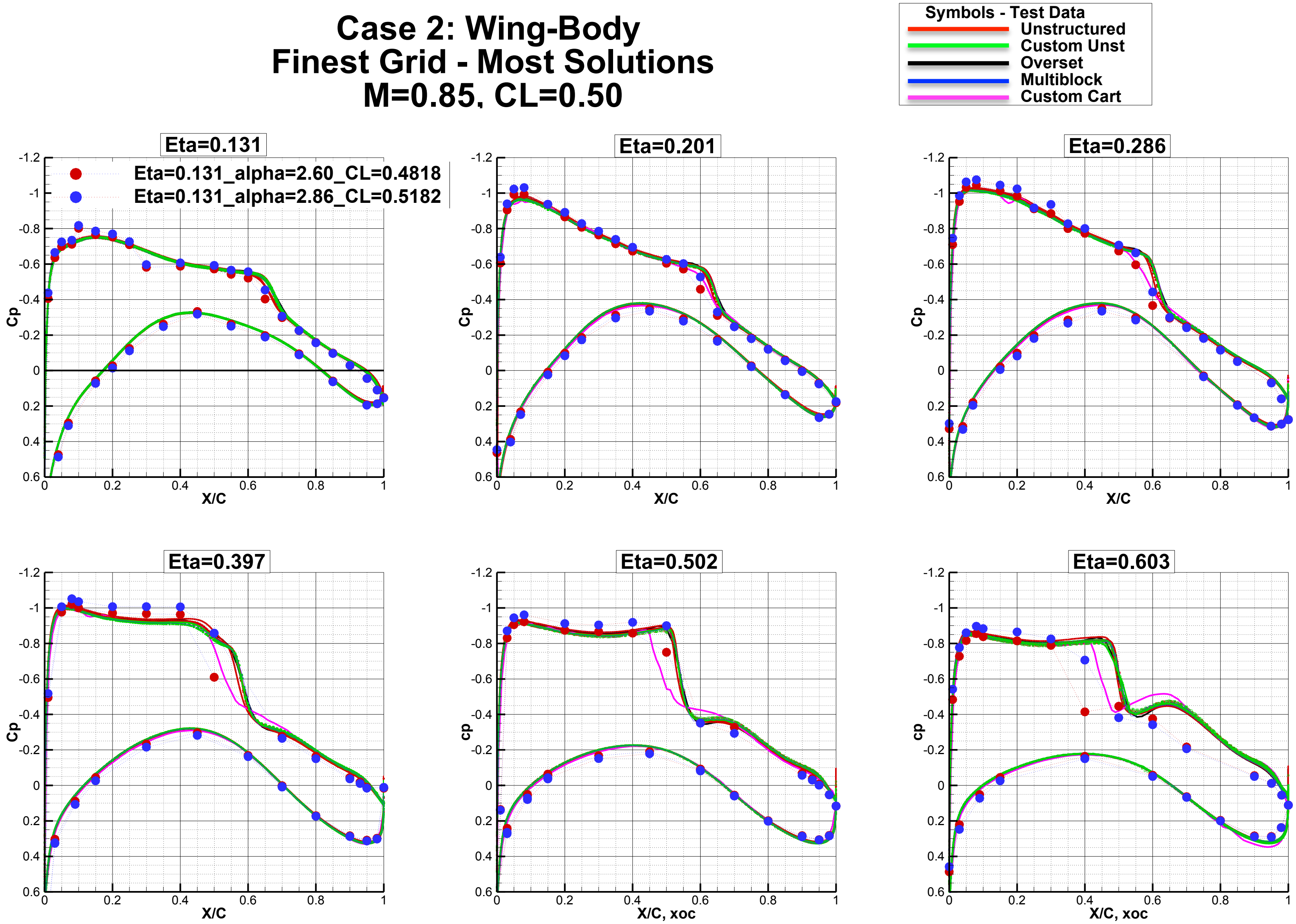
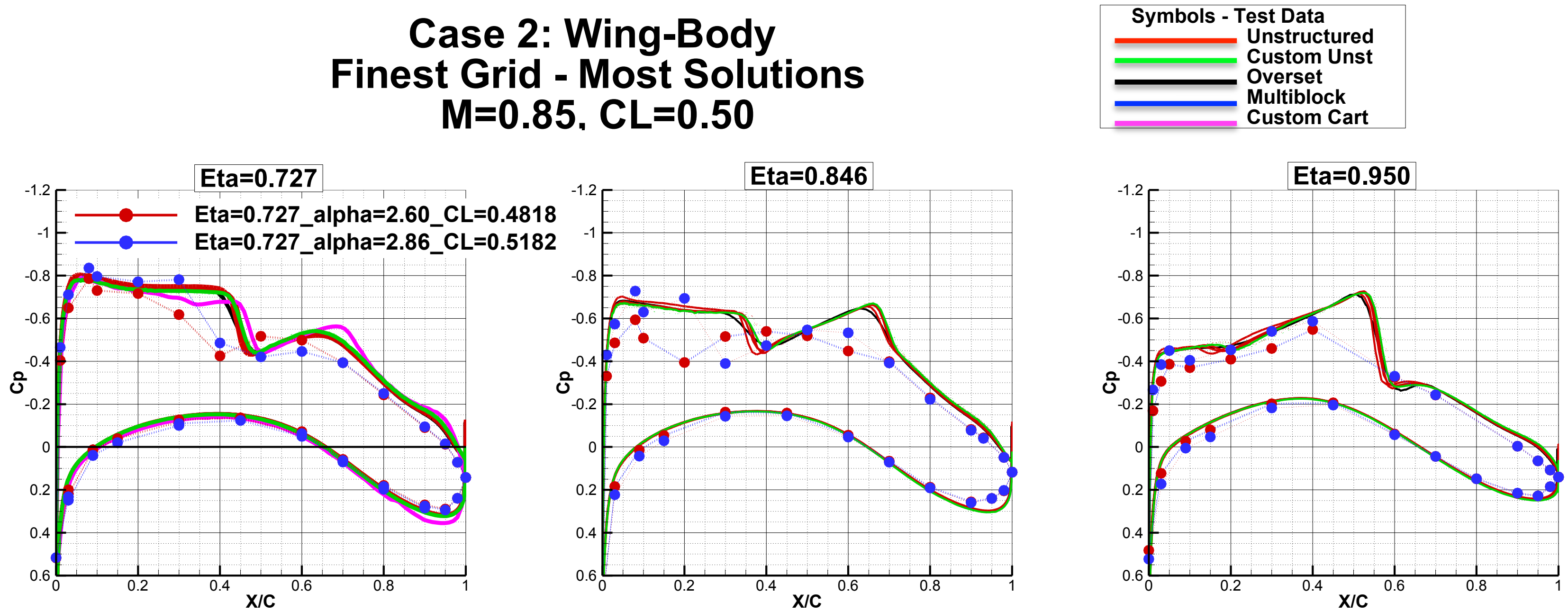
Case 2: Wing-Body
Finest Grid - Most Solutions
M=0.85, CL=0.50



Case 2: Wing-Body
Finest Grid - Most Solutions
M=0.85, CL=0.50



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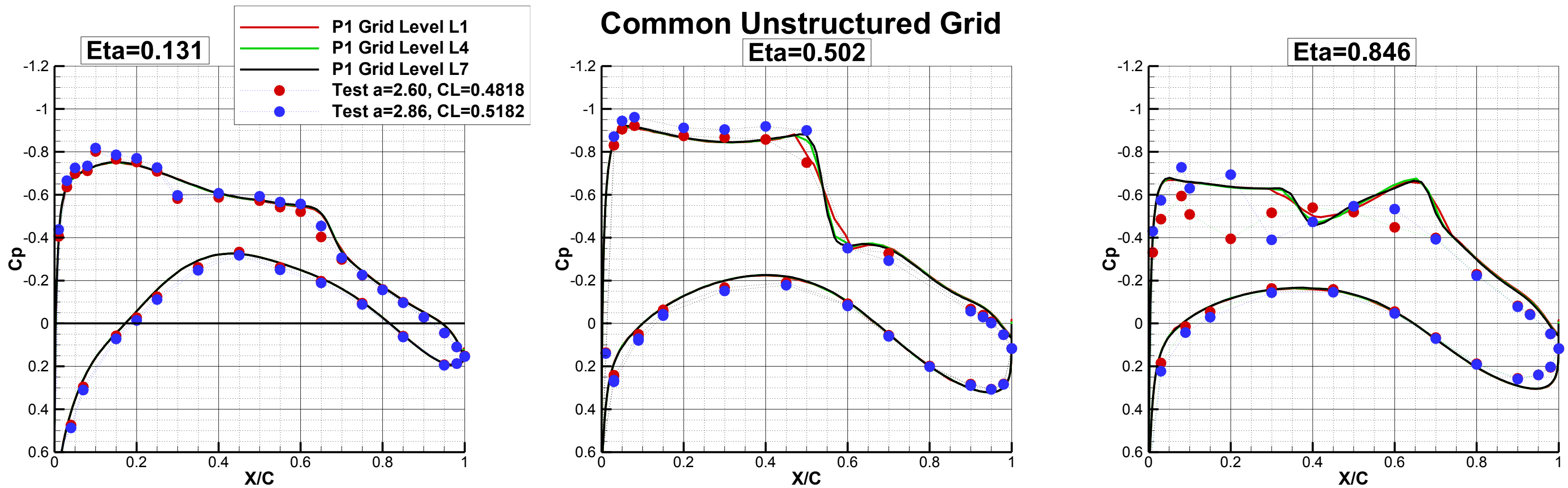
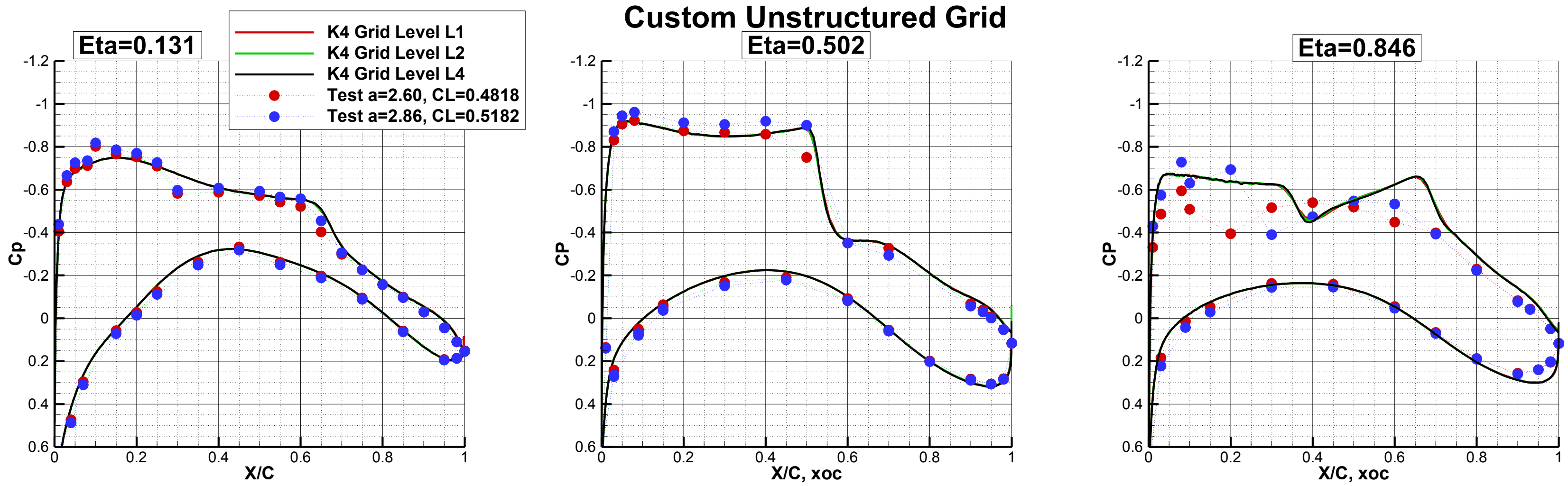
Case 2: Wing-Body Pressure Distributions
Grid Convergence History
M=0.85, CL=0.50

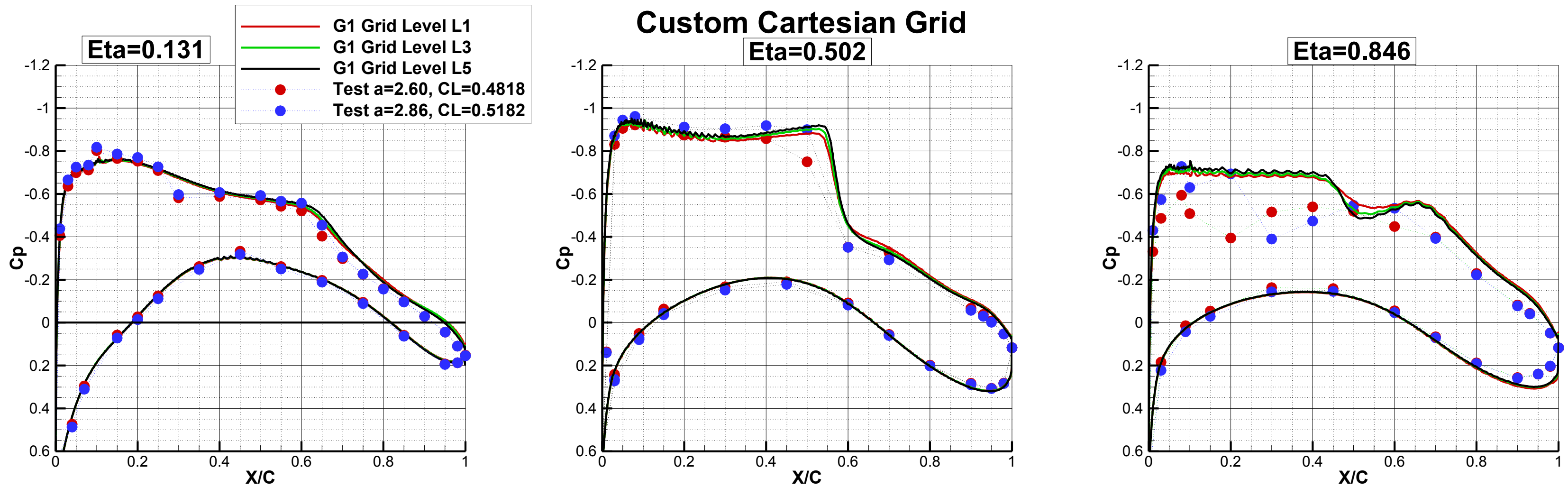
Common Unstructured Grid

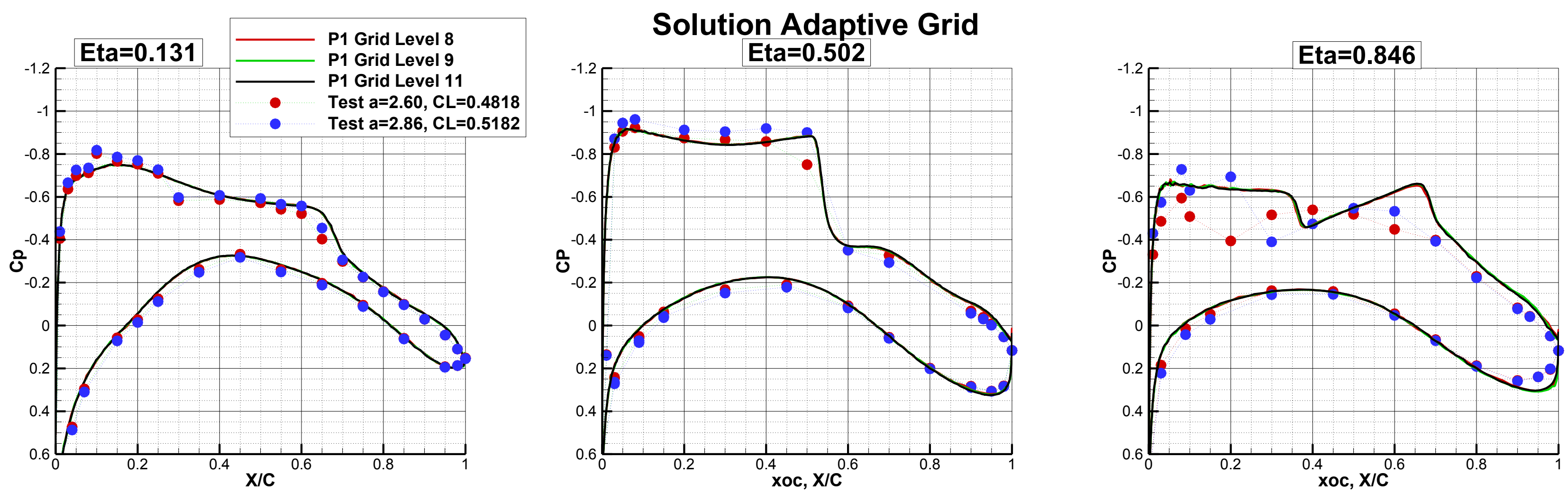


Custom Unstructured Grid

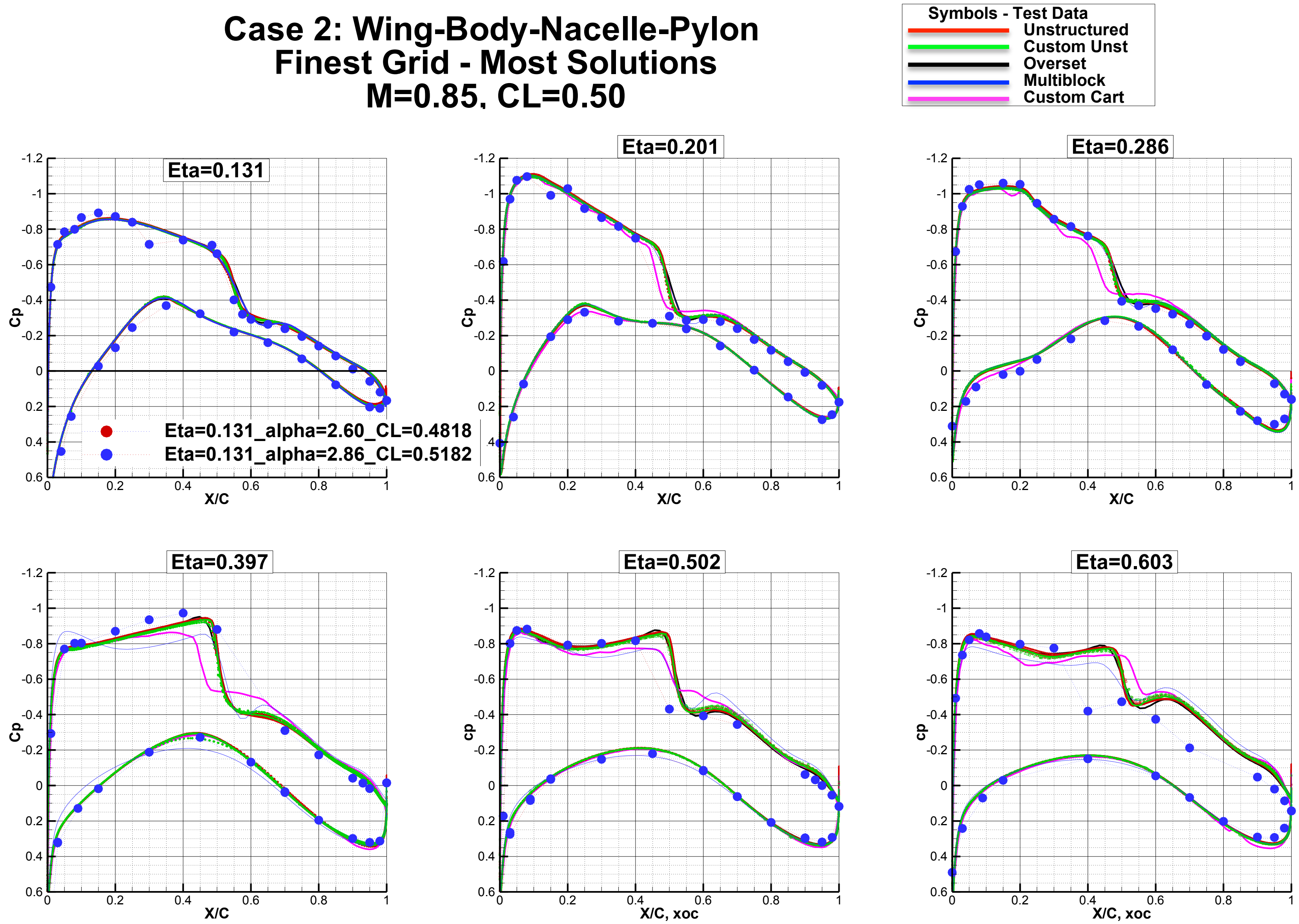


Case 2: Wing-Body Pressure Distributions
Grid Convergence History
M=0.85, CL=0.50

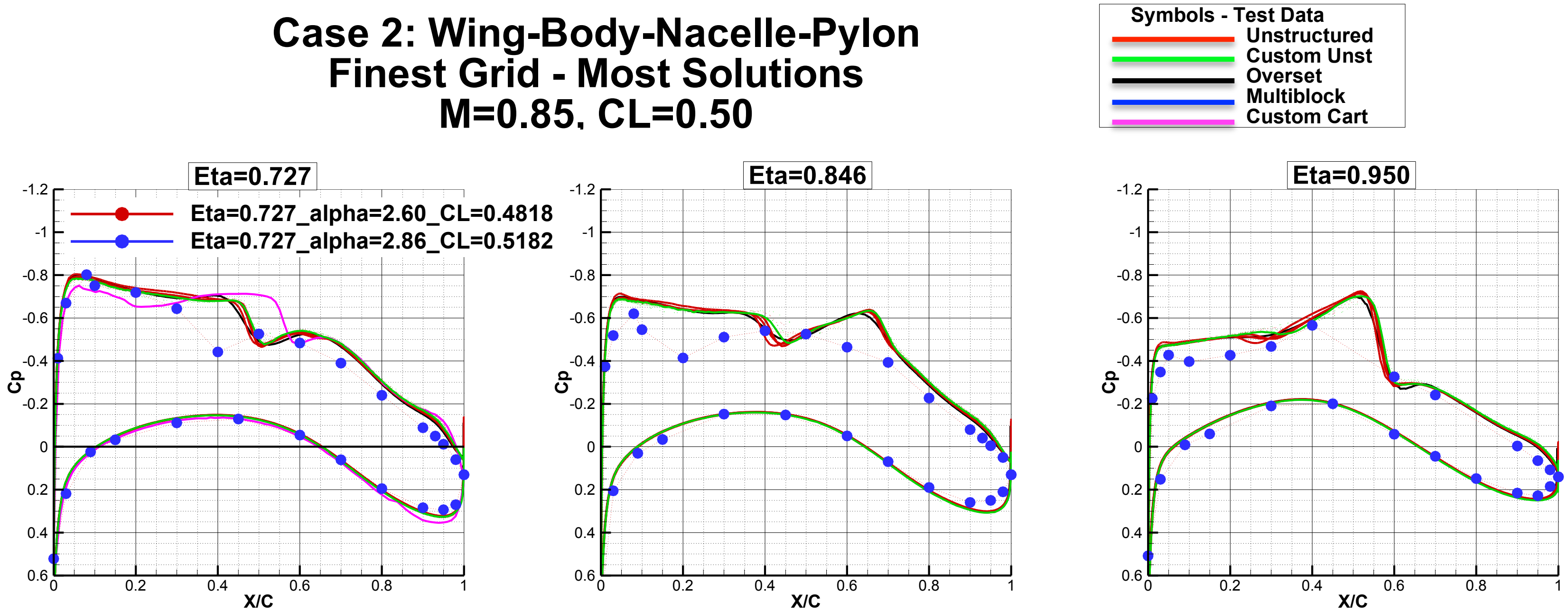




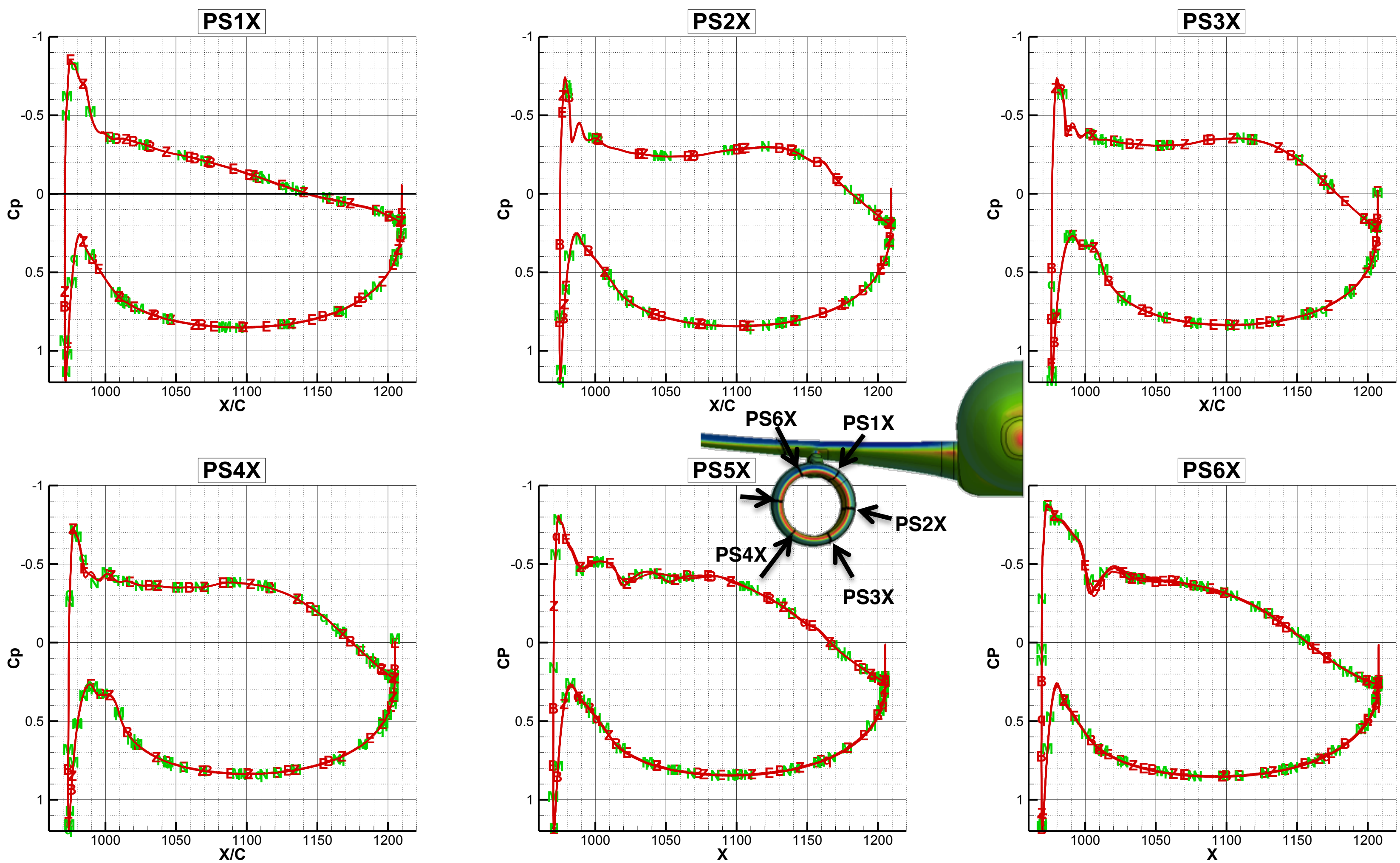
Case 2: Wing-Body-Nacelle-Pylon
Finest Grid - Most Solutions
M=0.85, CL=0.50



Case 2: Wing-Body-Nacelle-Pylon
Finest Grid - Most Solutions
M=0.85, CL=0.50



Case 2: Wing-Body-Nacelle-Pylon - Nacelle Pressures
Finest Grid
M=0.85, CL=0.50



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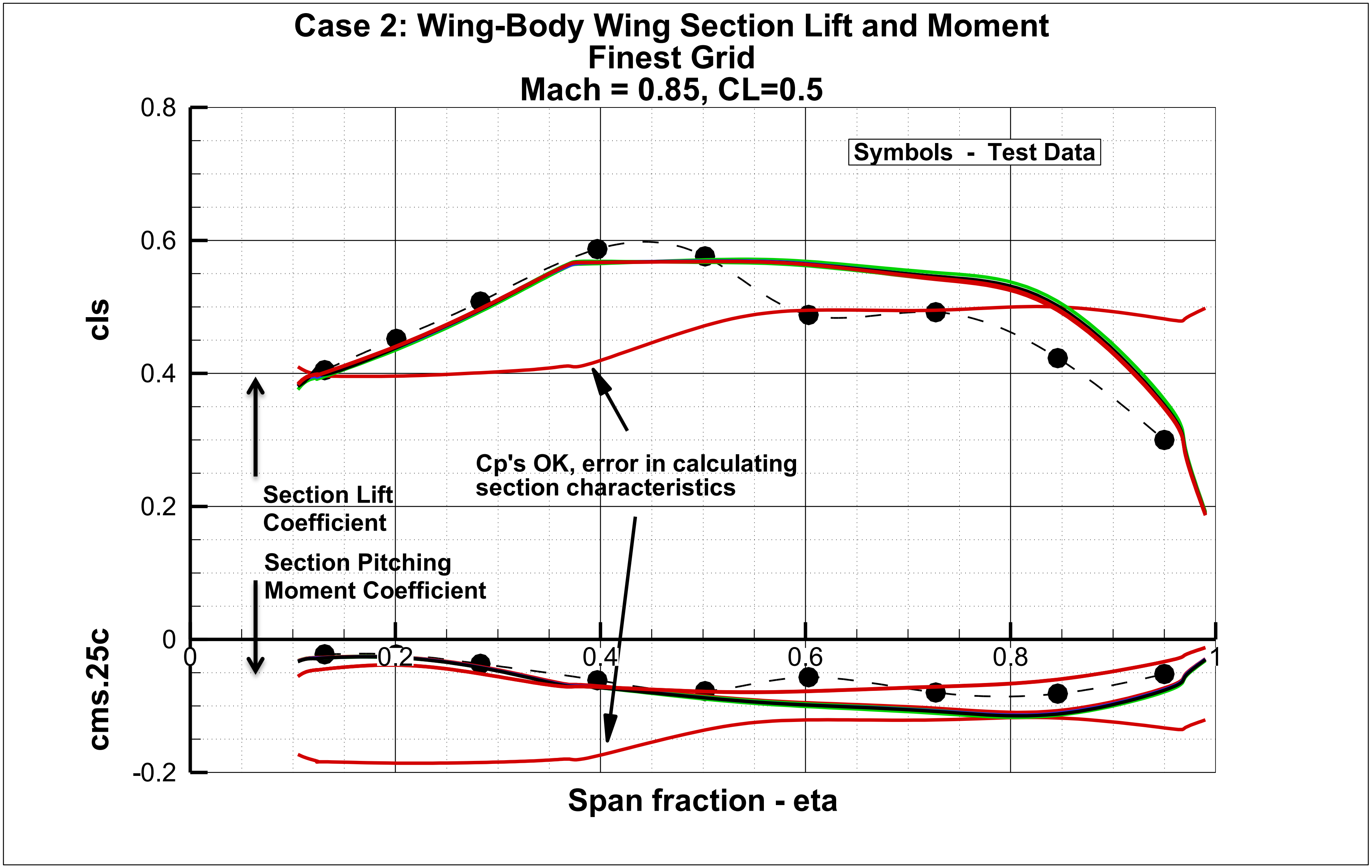

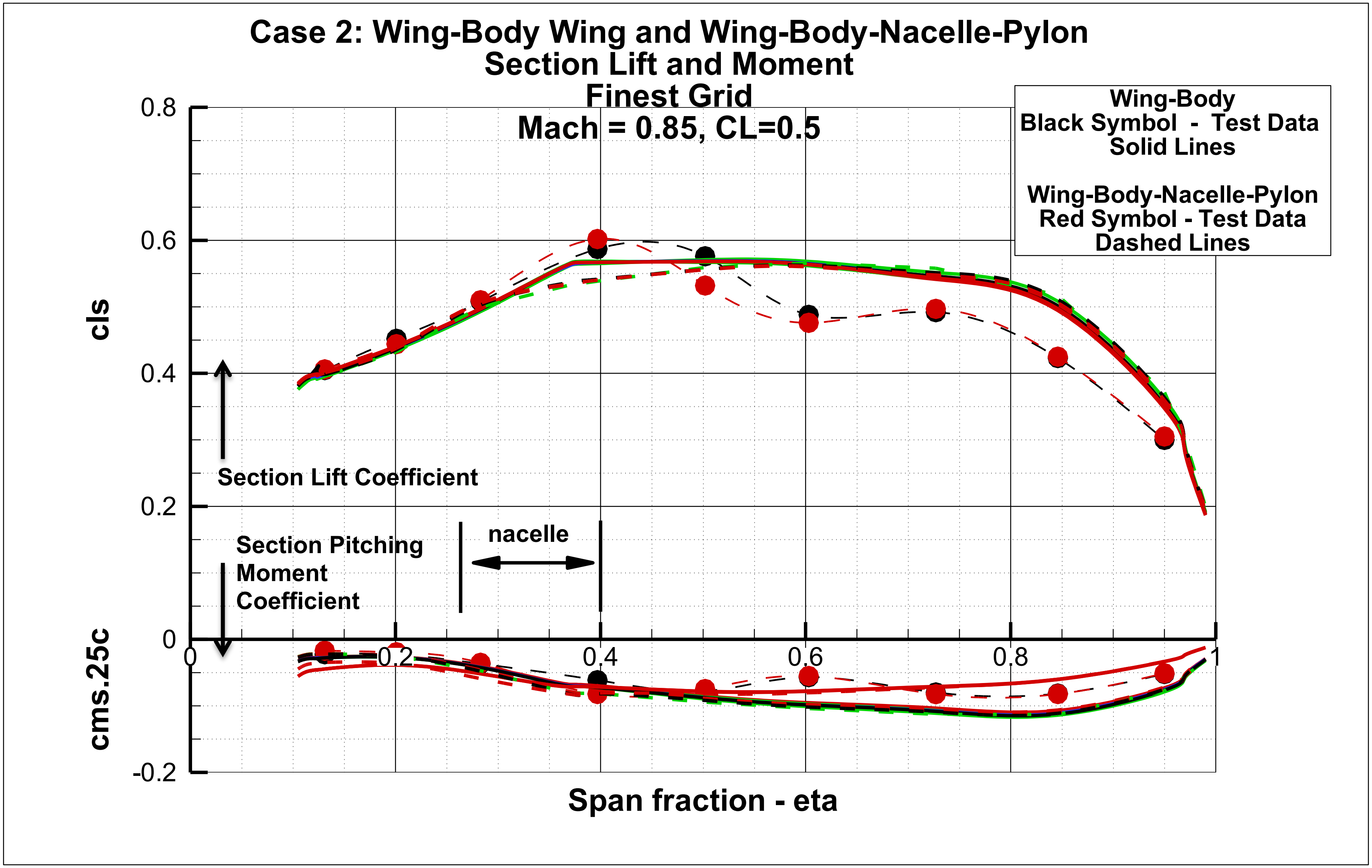
Case 2: Wing-Body Wing and Wing-Body-Nacelle-Pylon
Section Lift and Moment
Finest Grid
Mach = 0.85, CL=0.5
Wing-Body
Black Symbol - Test Data
Solid Lines
Wing-Body-Nacelle-Pylon
Red Symbol - Test Data
Dashed Lines
cls
cms.25c
Section Lift Coefficient
Section Pitching
Moment
Coefficient
nacelle
0.8
0.6
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Span fraction - eta

Observations from Case 2 Results:

- We are getting better!
- Nacelle-Pylon drag increment prediction within experimental variation.
- Scatter for k-e Lam-Bremhorst and LBM-VLES models cannot be separated from grid type.
- With the exception of one set of Cartesian grid results very little differences seen in wing or nacelle pressure distributions, or in wing section lift and pitching moment due to grid type, turbulence model, or convergence level.

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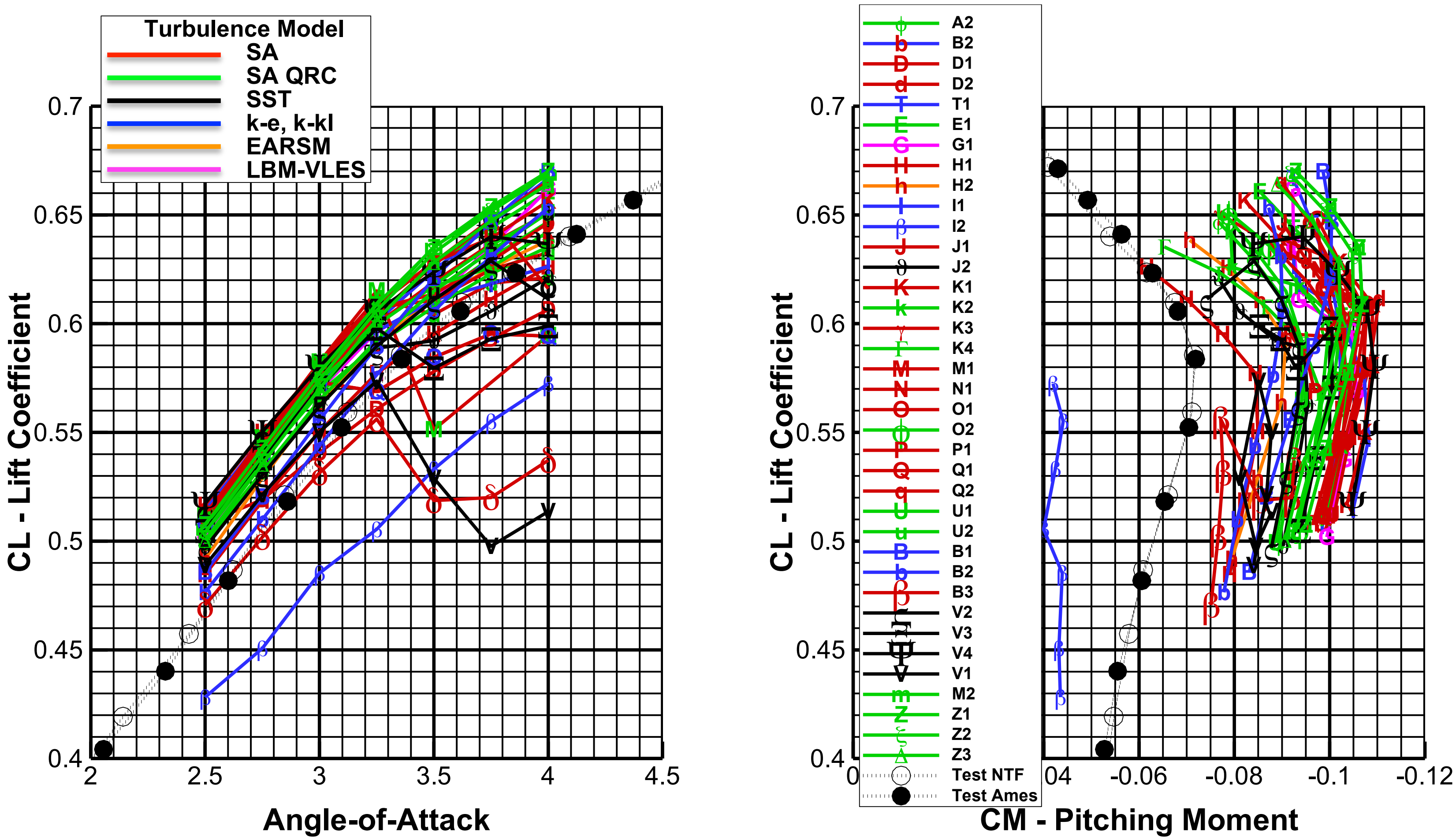
Case 3: CRM WB Static Aero-Elastic Effect:

- NASA Common Research Model, Wing-Body
- Mach=0.85:
  - α=2.50°, 2.75 °, 3.00 °, 3.25 °, 3.50 °, 3.75 °, 4.00 °
- Grid Resolution Level:
  - 3) Medium,
- Chord Reynolds Number: 5×10^6
- Measured Static Aero-Elastic Wing Deformation at each angle of attack

Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
All Solutions
Turbulence Model



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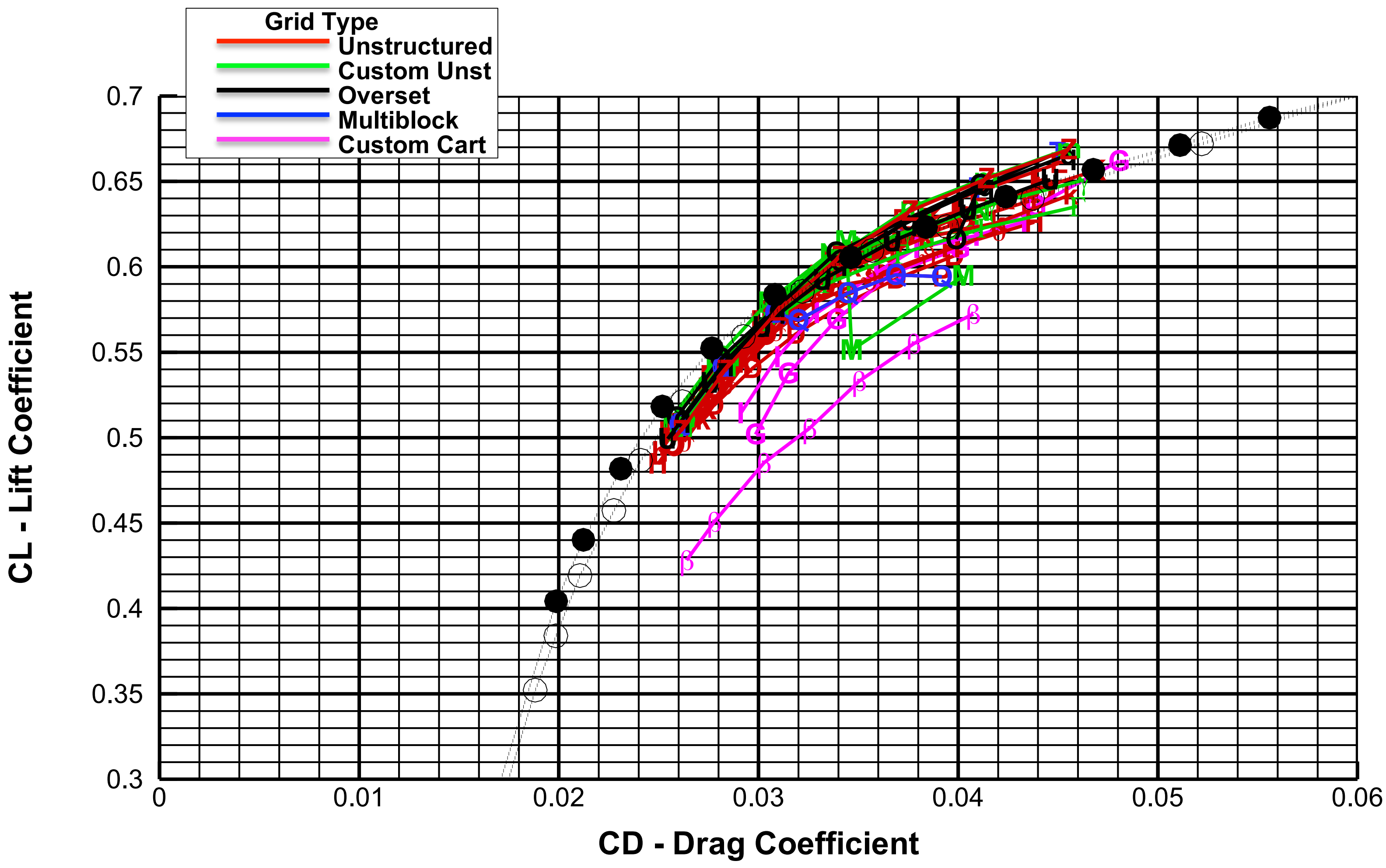
Case 3: Wing-Body Drag w/Static Aeroelastics
All Soutions - Grid Type



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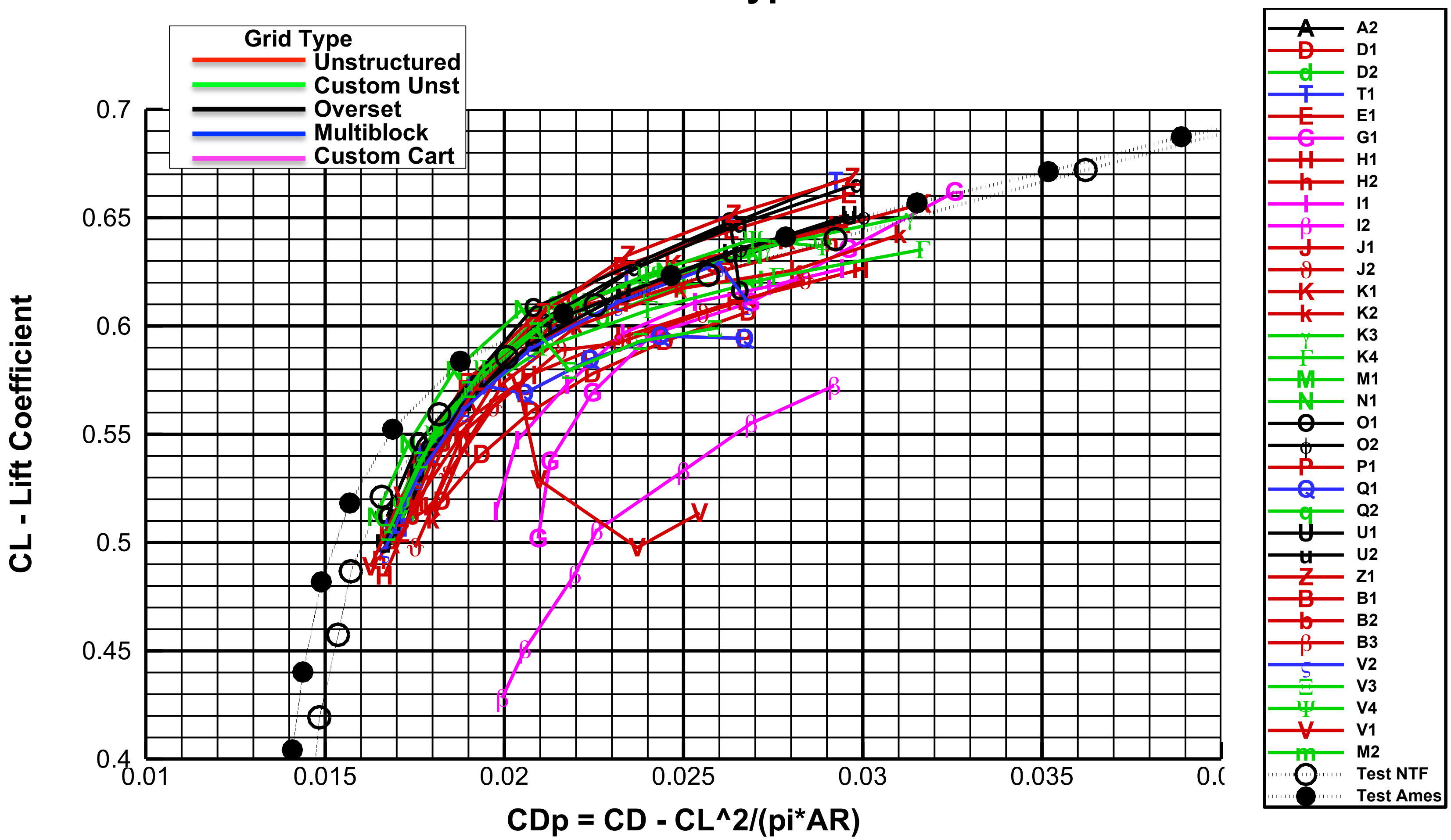
Case 3: Drag minus Idealized Induced Drag
Wing-Body w/Static Aeroelastics
All Solutions
Grid Type



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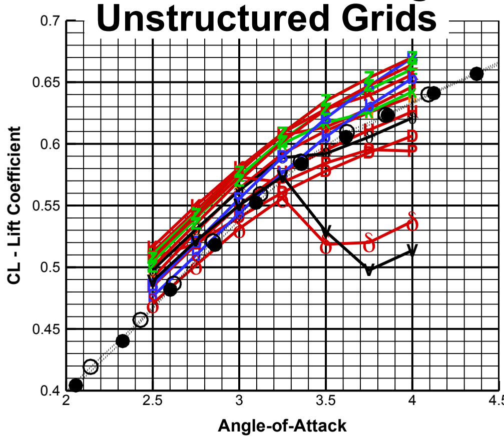
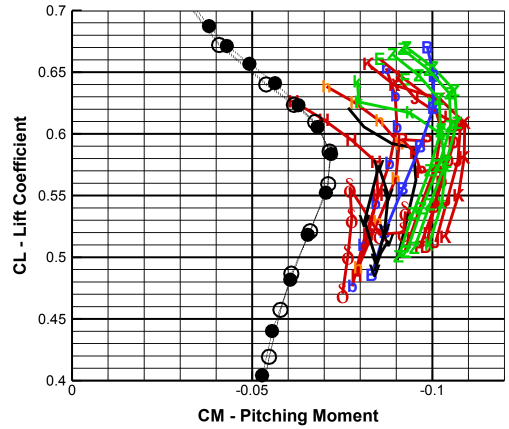
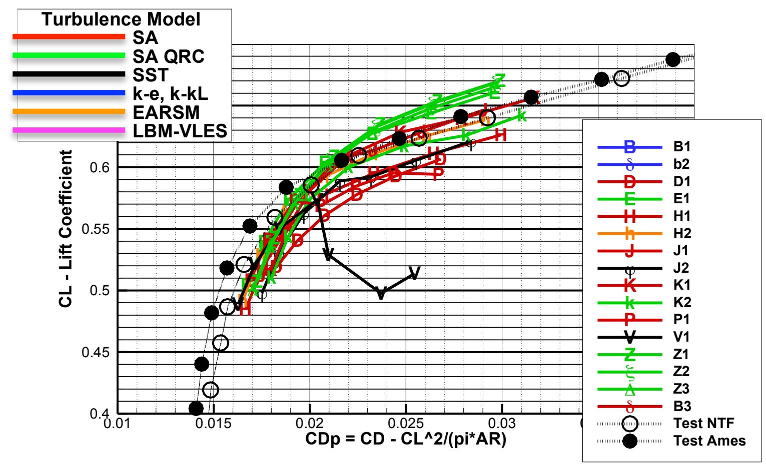
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Grid Type & Turbulence Model

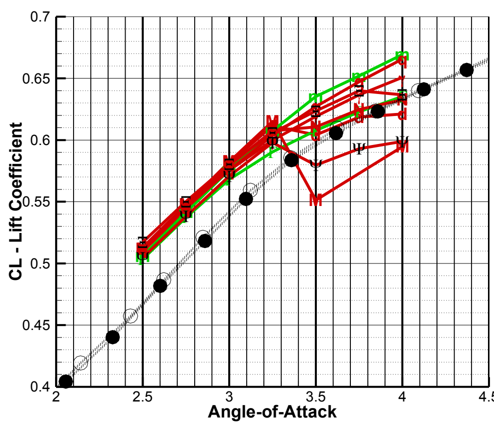
Geolab and Boeing Unstructured Grids

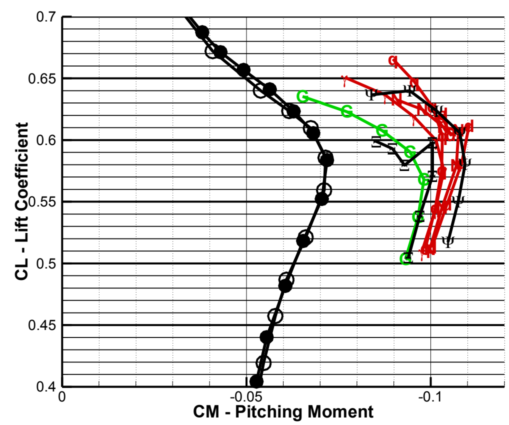


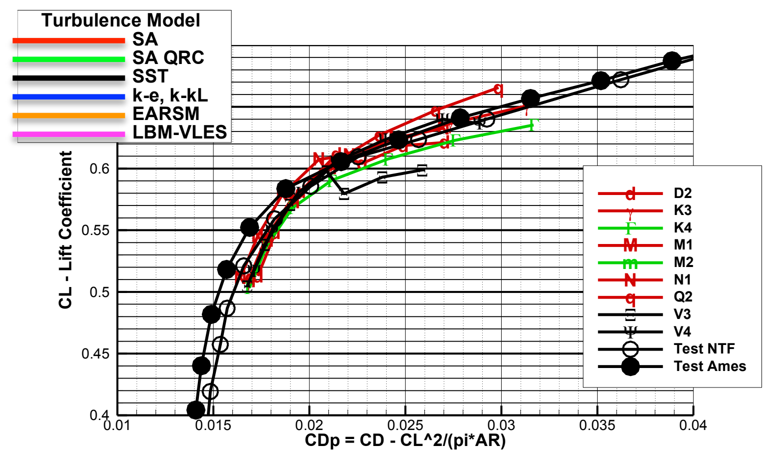




Custom Unstructured Grids

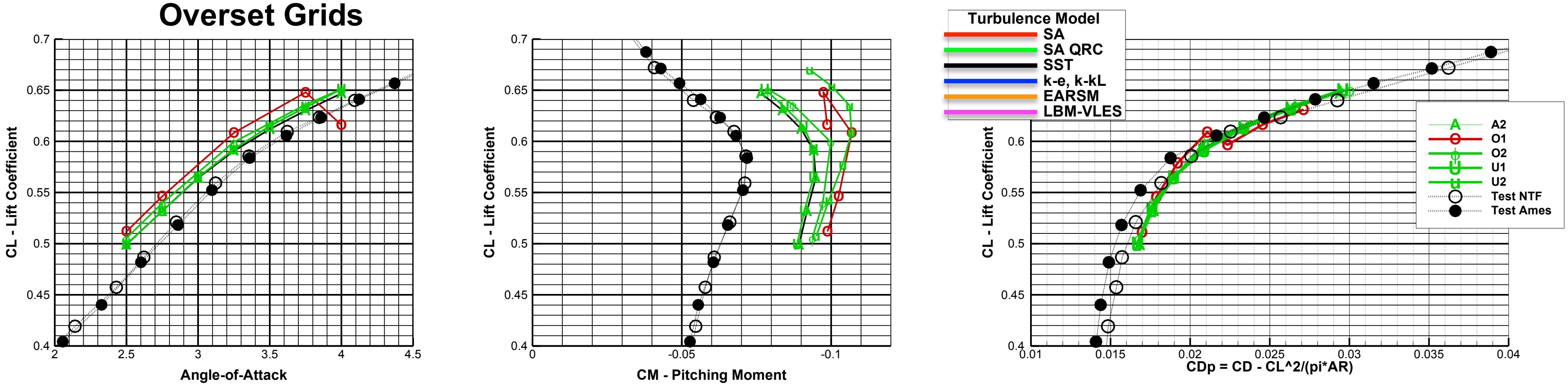




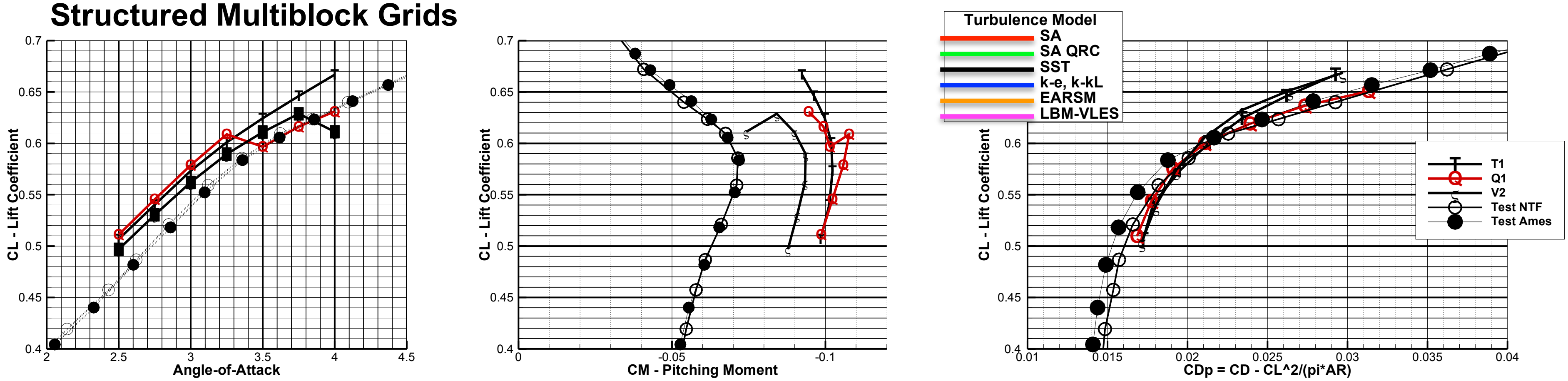


Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Grid Type & Turbulence Model

Overset Grids



Structured Multiblock Grids



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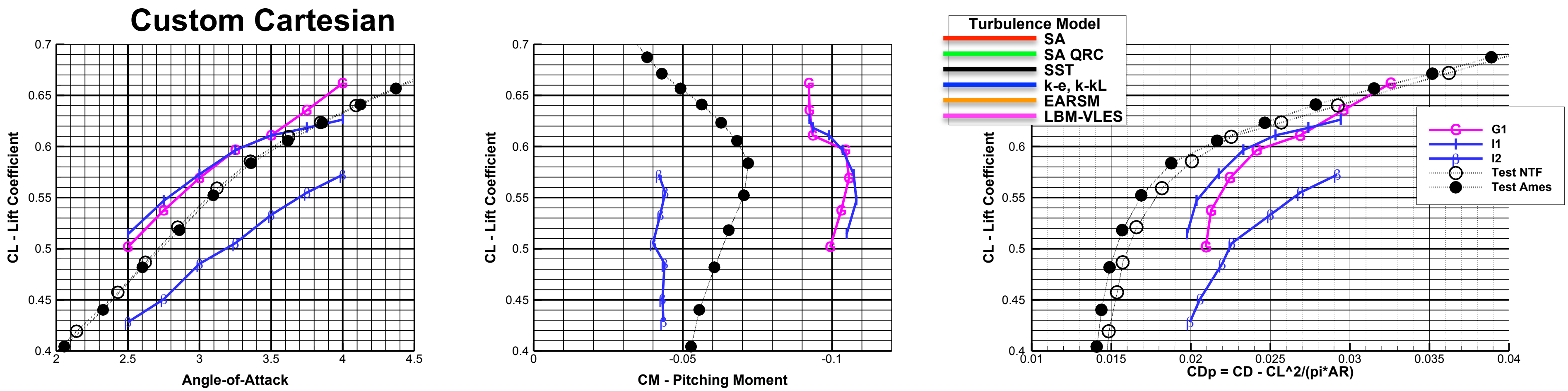
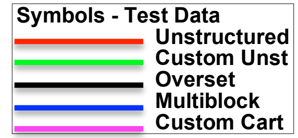
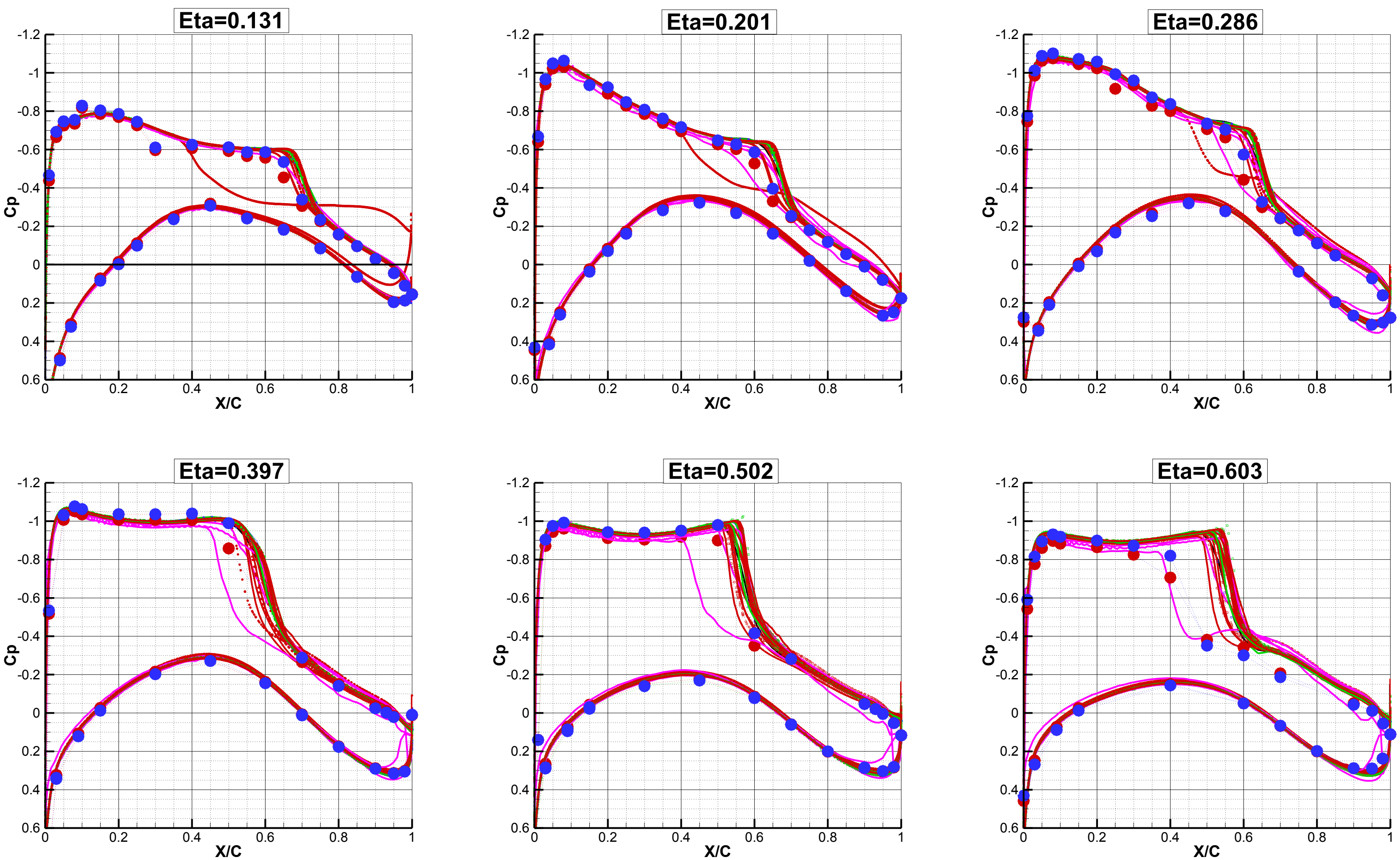
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Grid Type & Turbulence Model



Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=3.0





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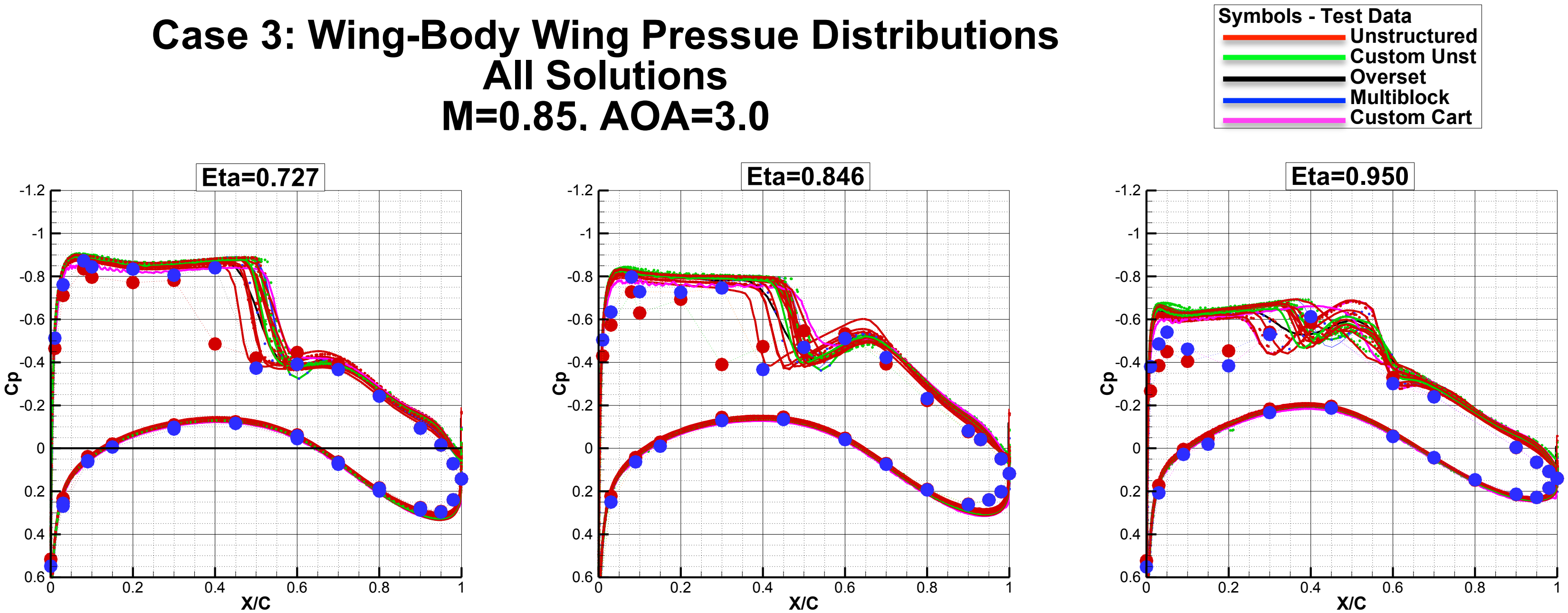
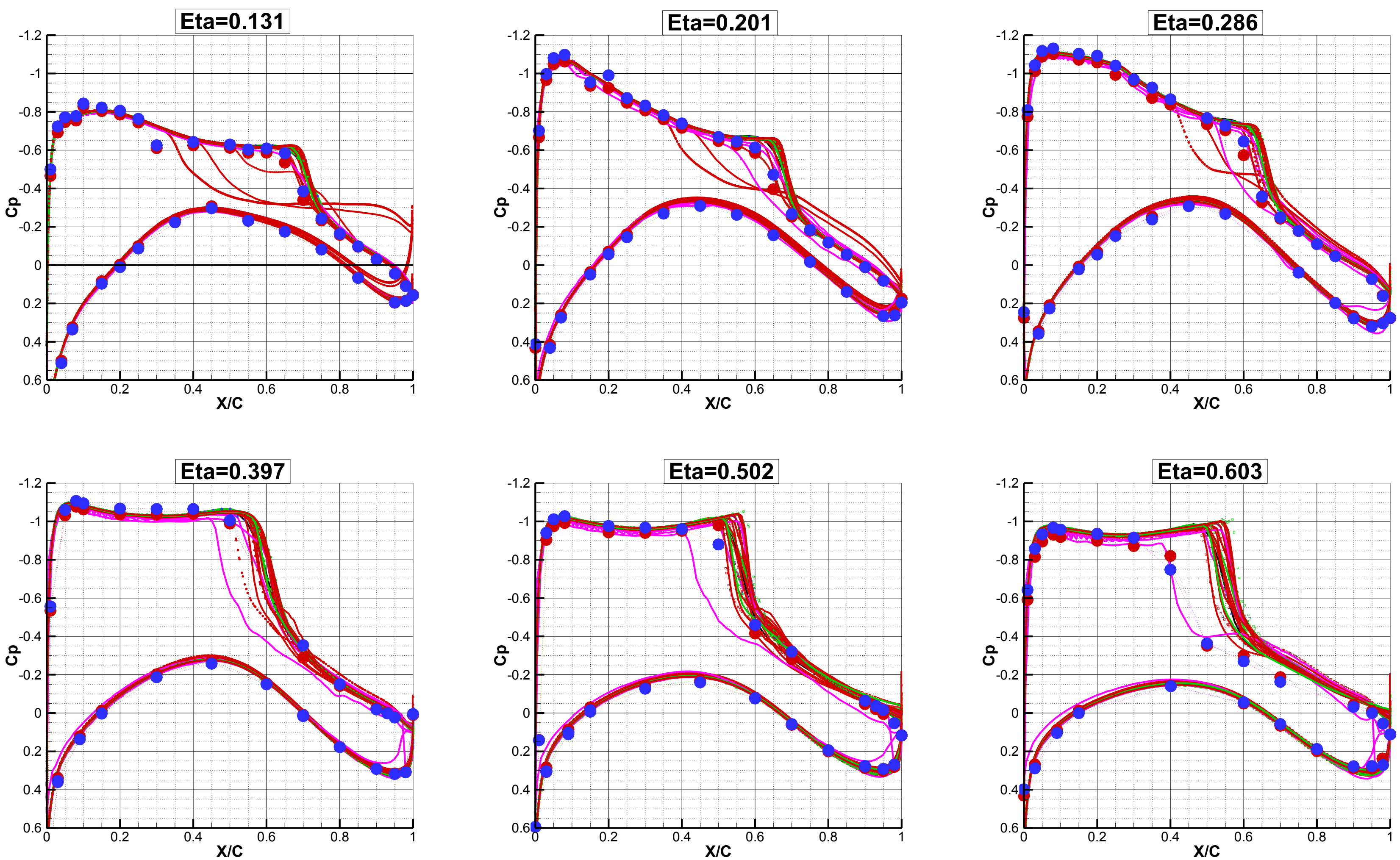
Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=3.0



Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85. AOA=3.25

Symbols - Test Data
Unstructured
Custom Unst
Overset
Multiblock
Custom Cart



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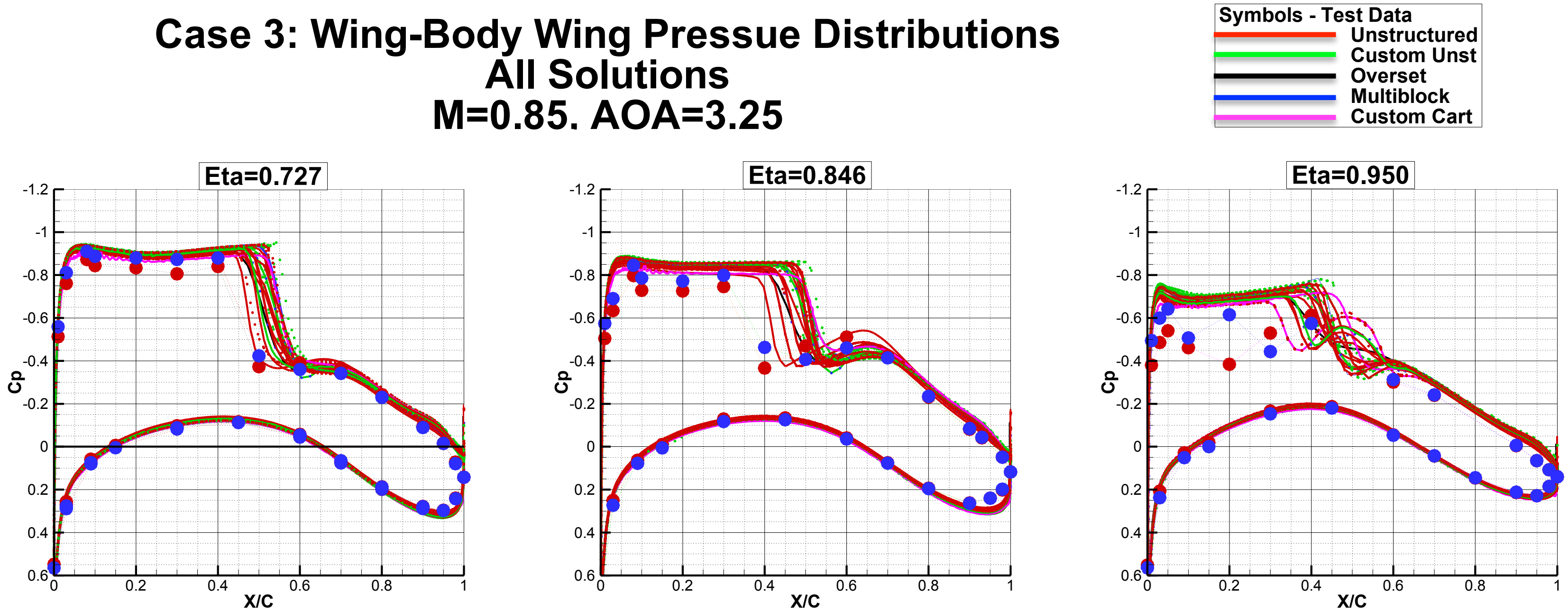
Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=3.25



Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=3.5

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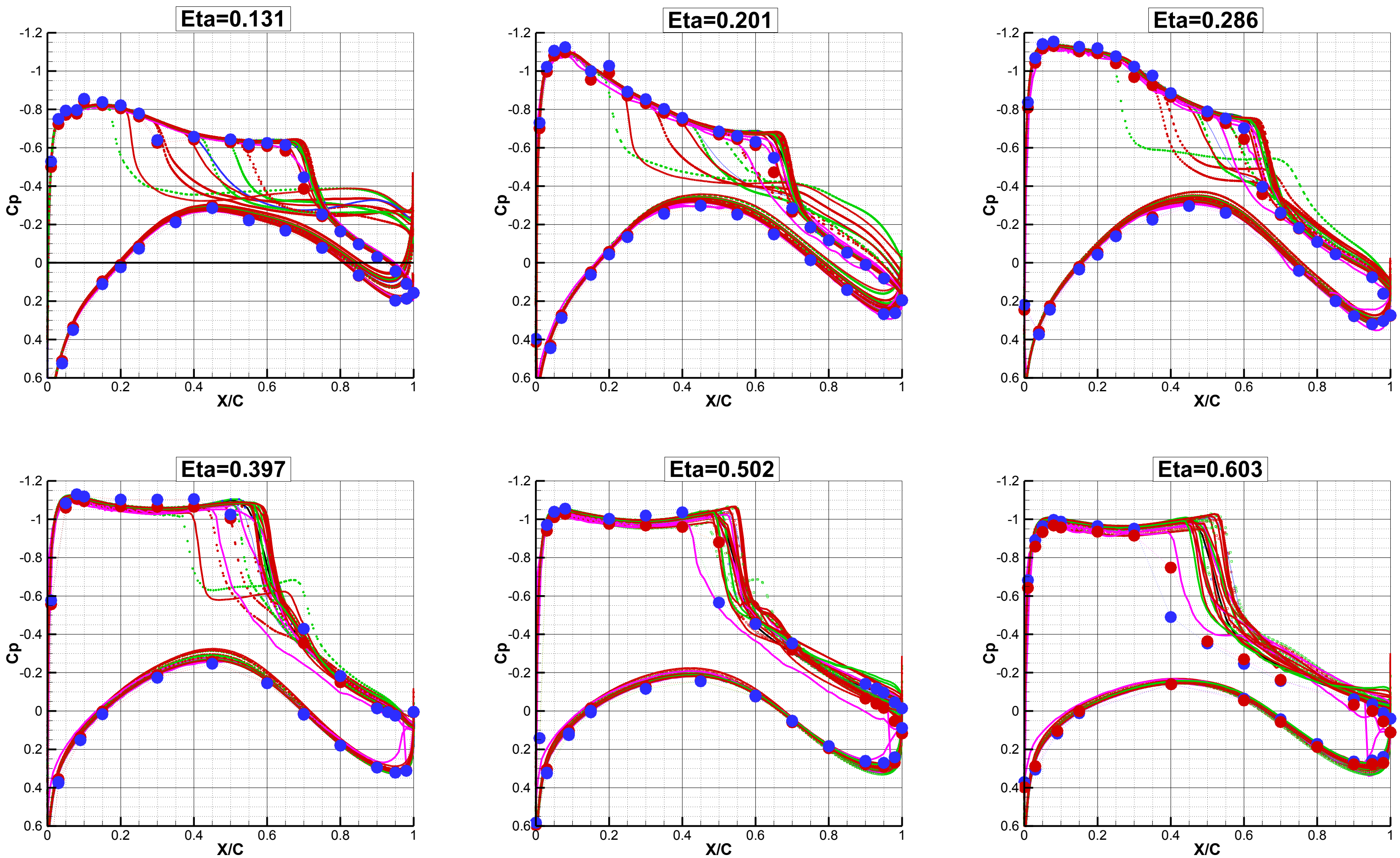
Custom Unst
Overset
Multiblock
Custom Cart



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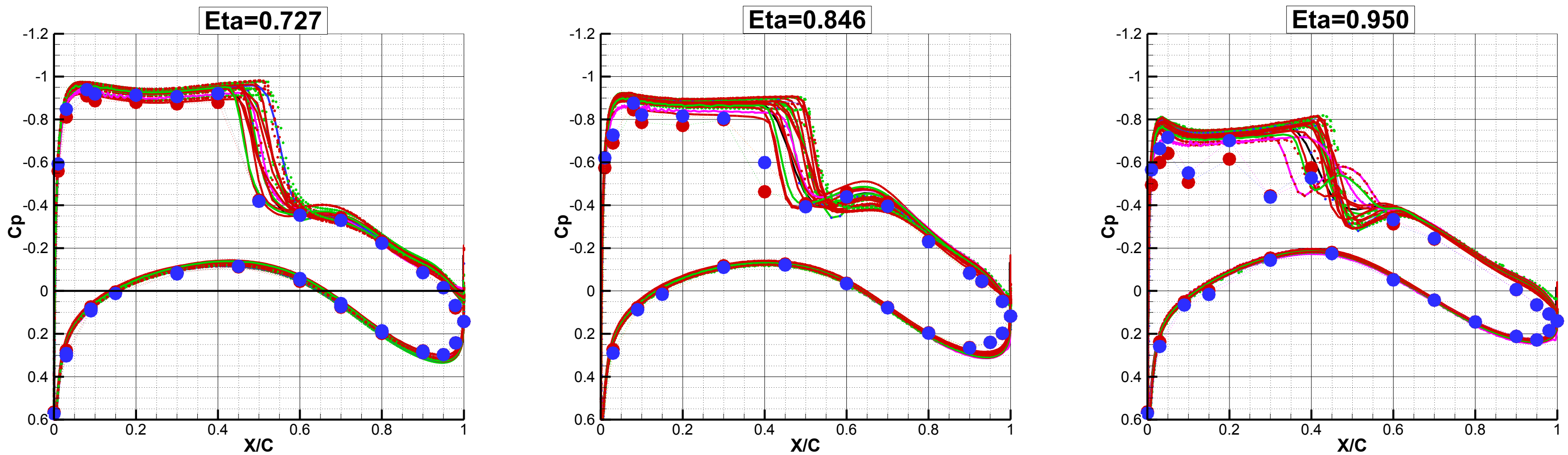
Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=3.5

Symbols - Test Data
Unstructured
Custom Unst
Overset
Multiblock
Custom Cart



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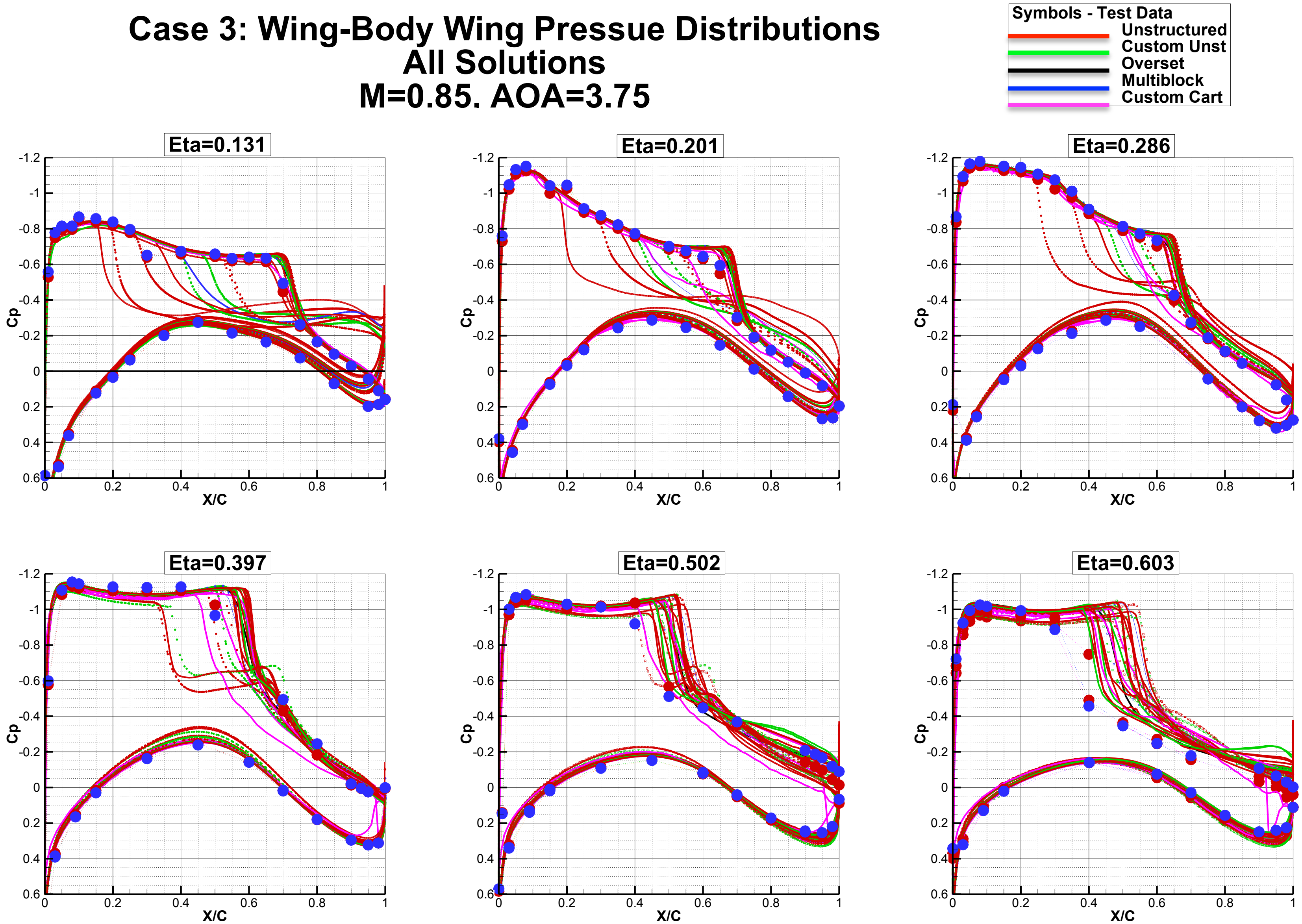
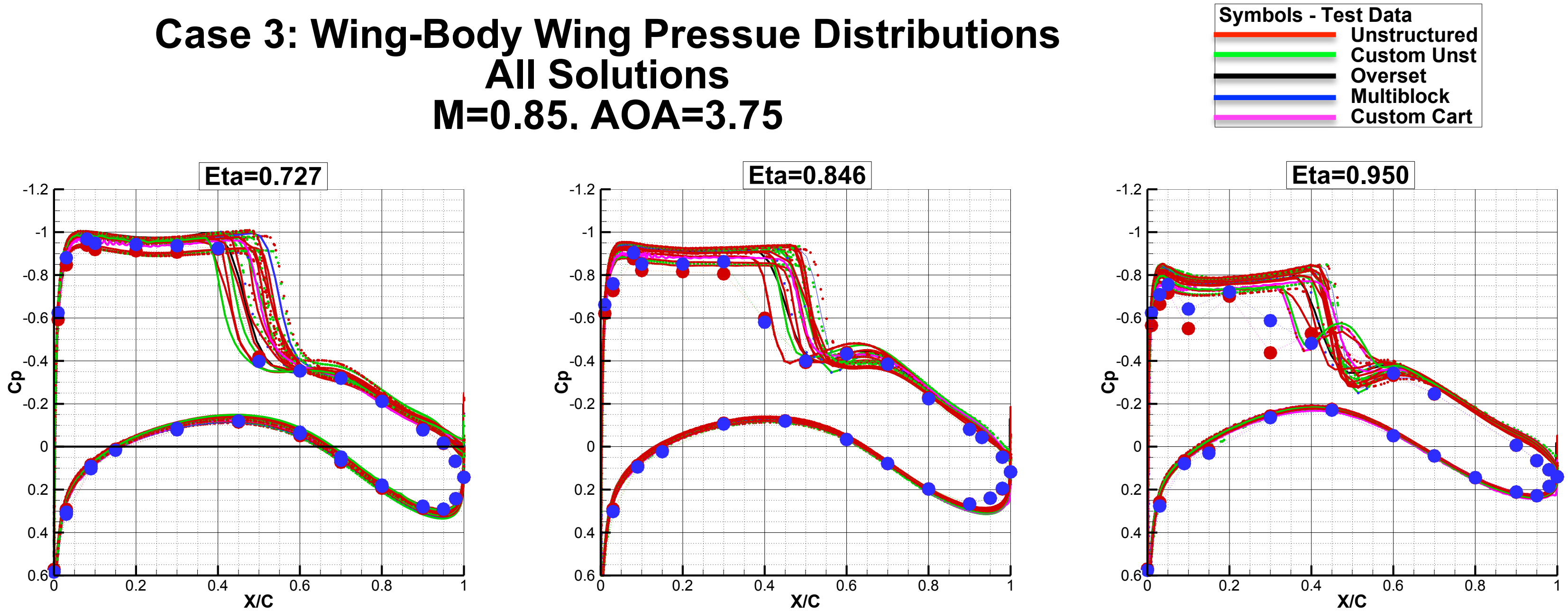
Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=3.75



Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=3.75



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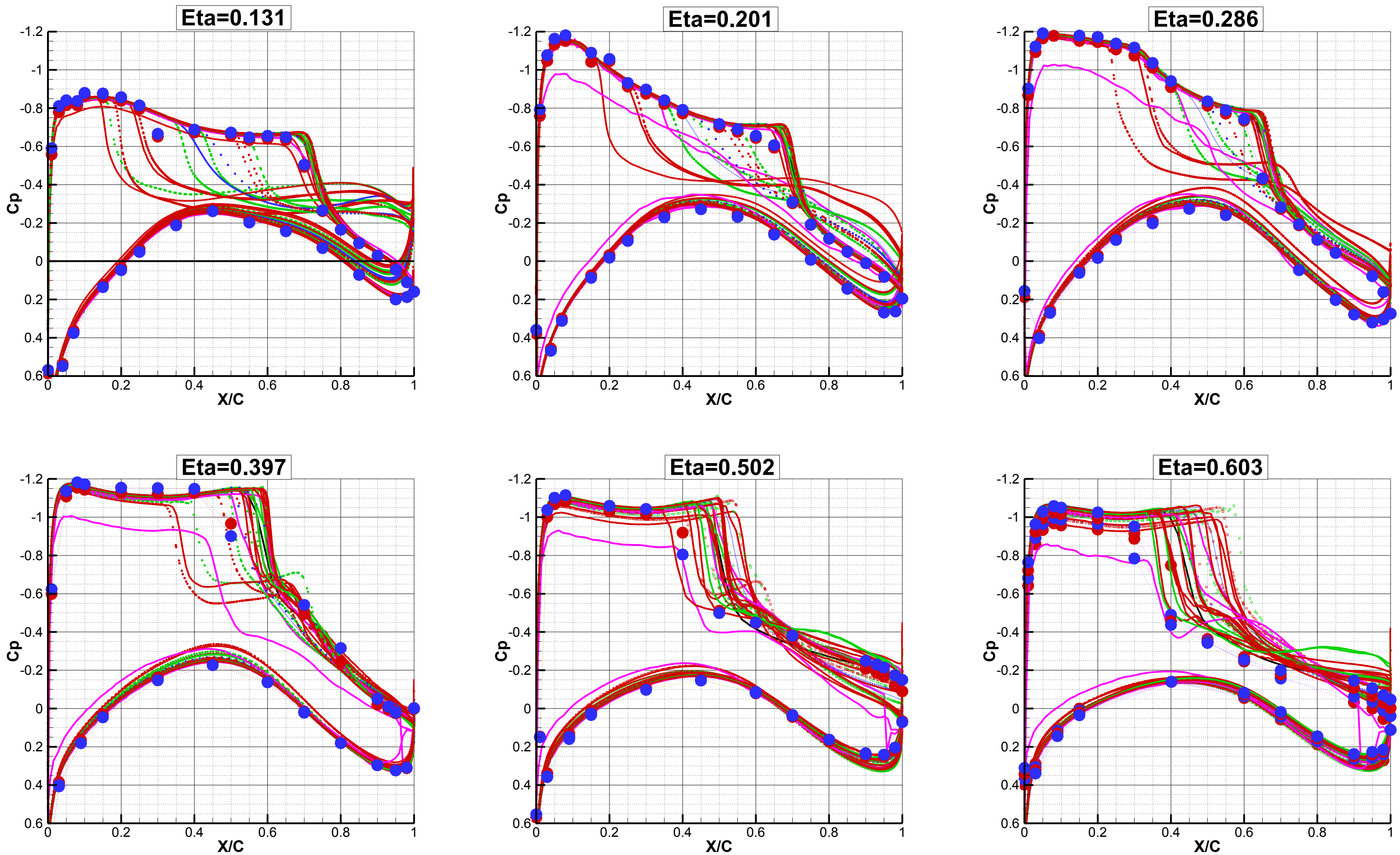
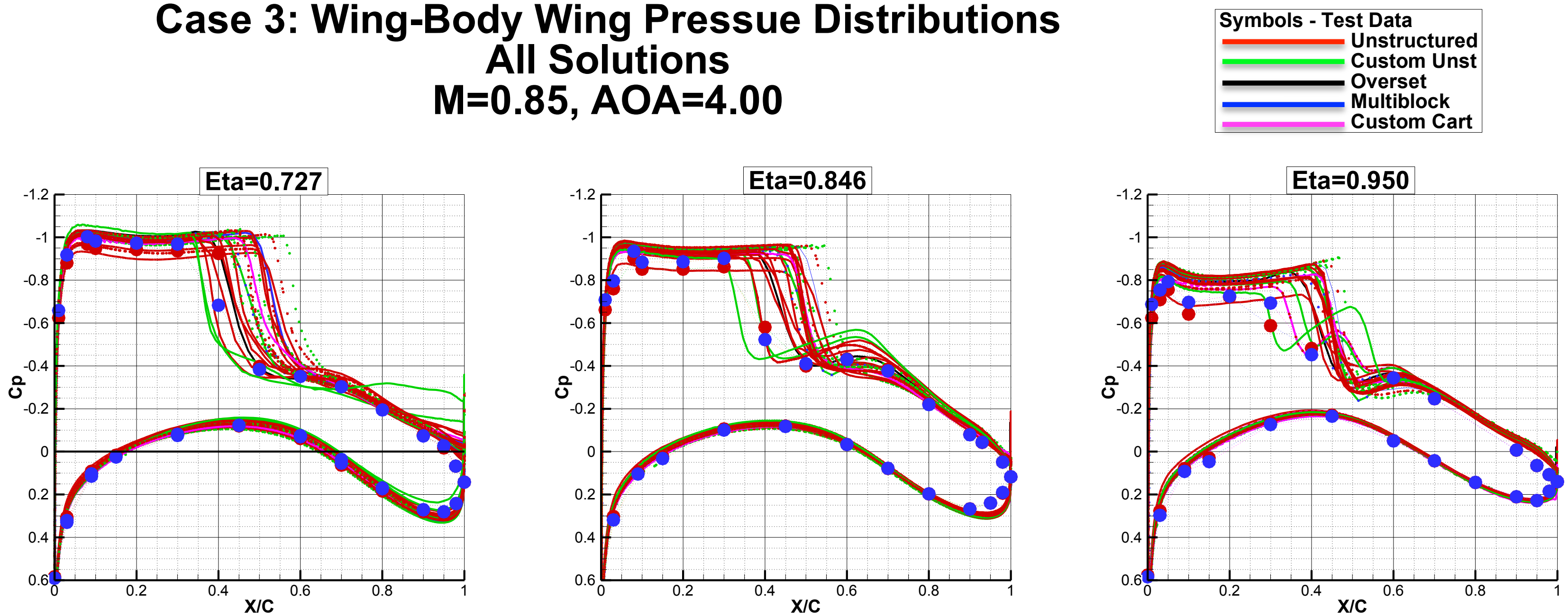
Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85. AOA=4.00

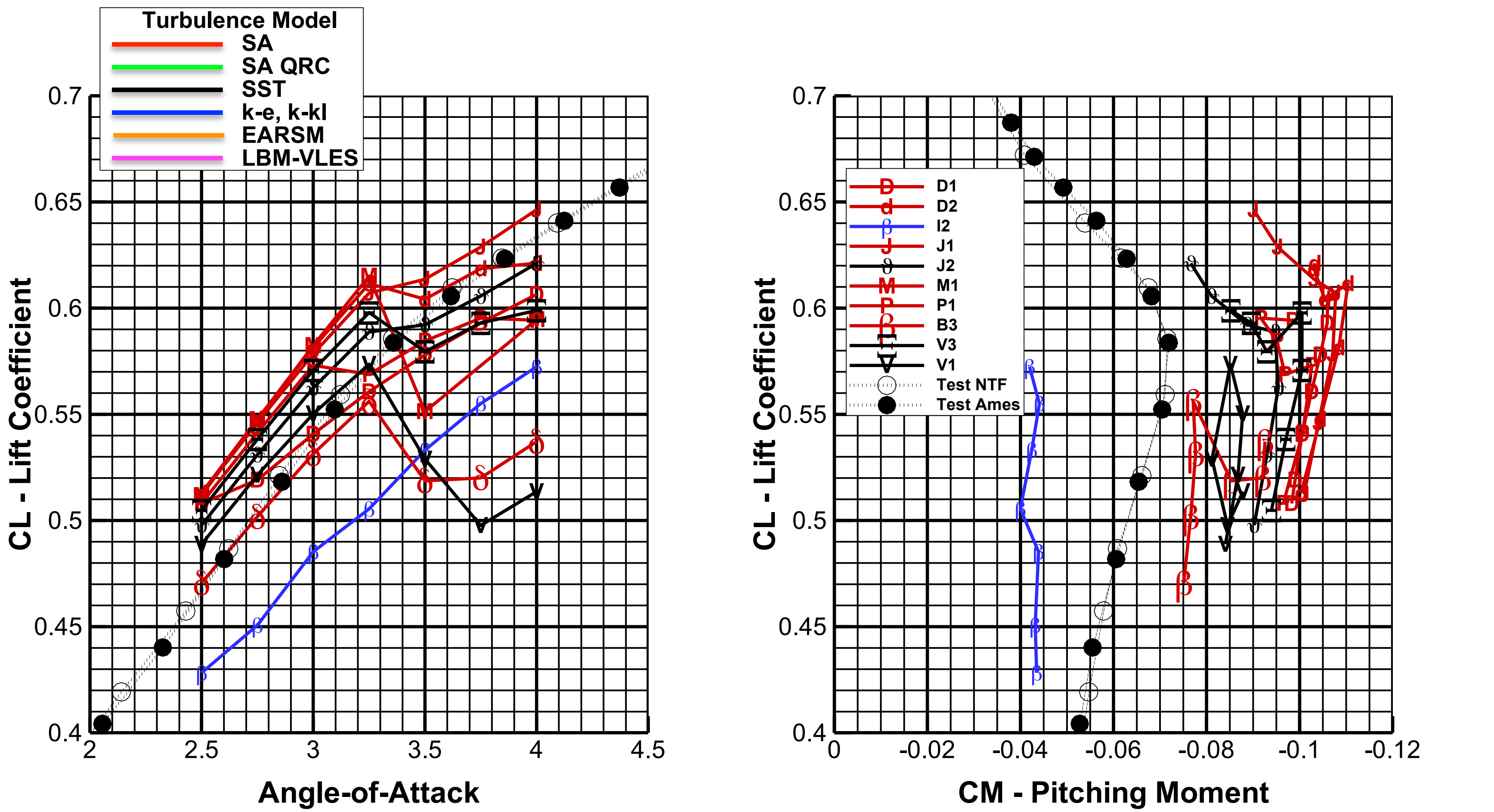
Symbols - Test Data
Unstructured
Custom Unst
Overset
Multiblock
Custom Cart



Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85, AOA=4.00



Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Outliers - CL Break at AOA=3.50 or Below
Turbulence Model



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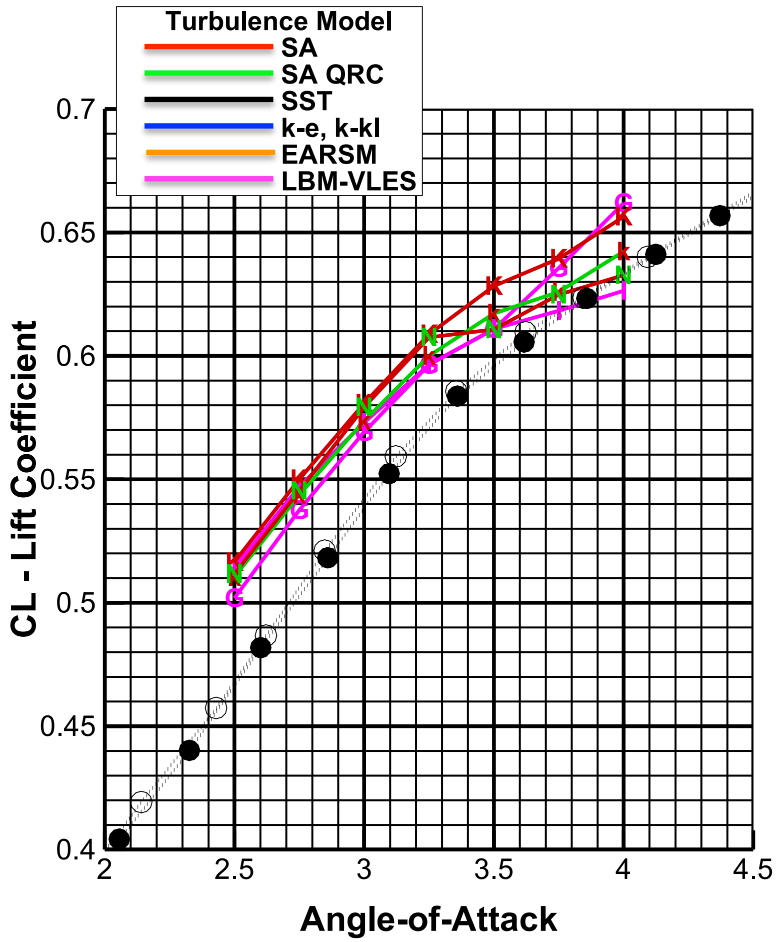
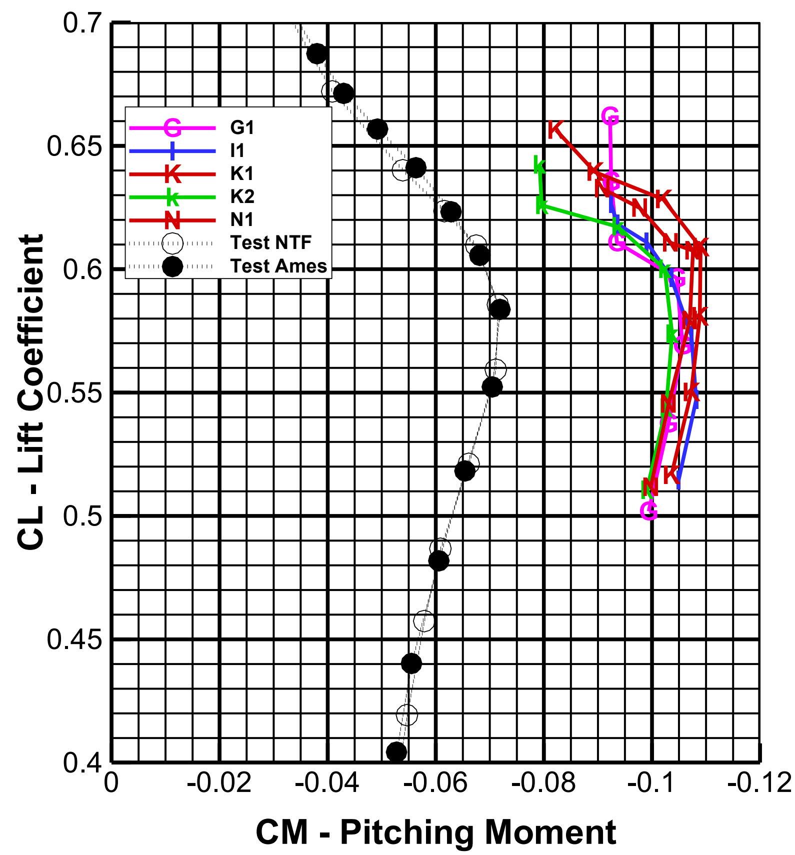
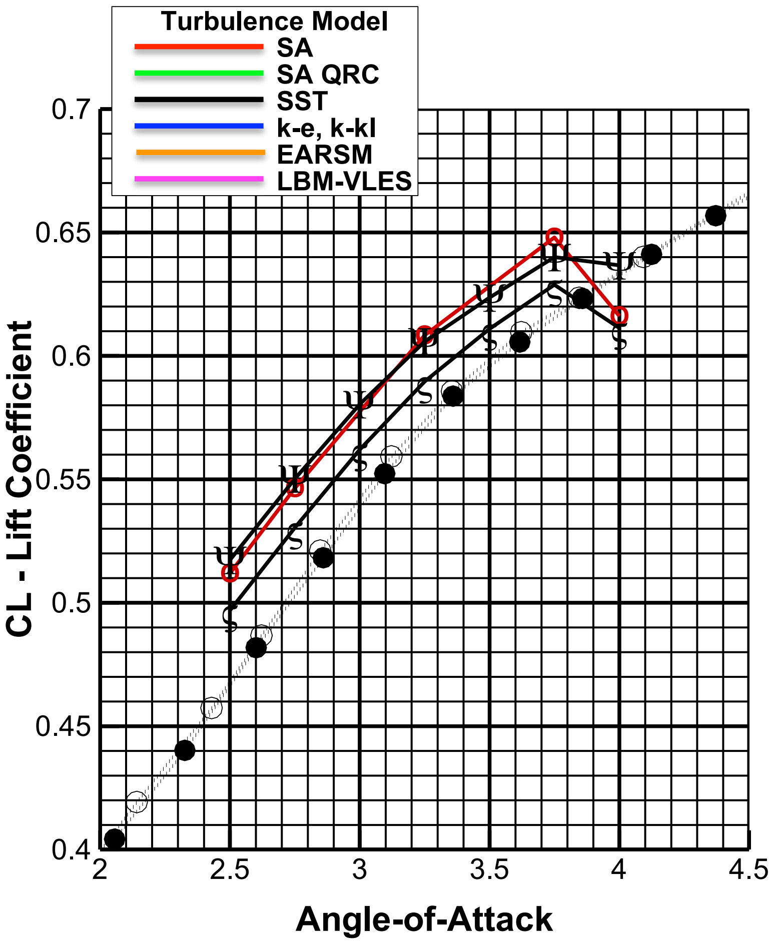
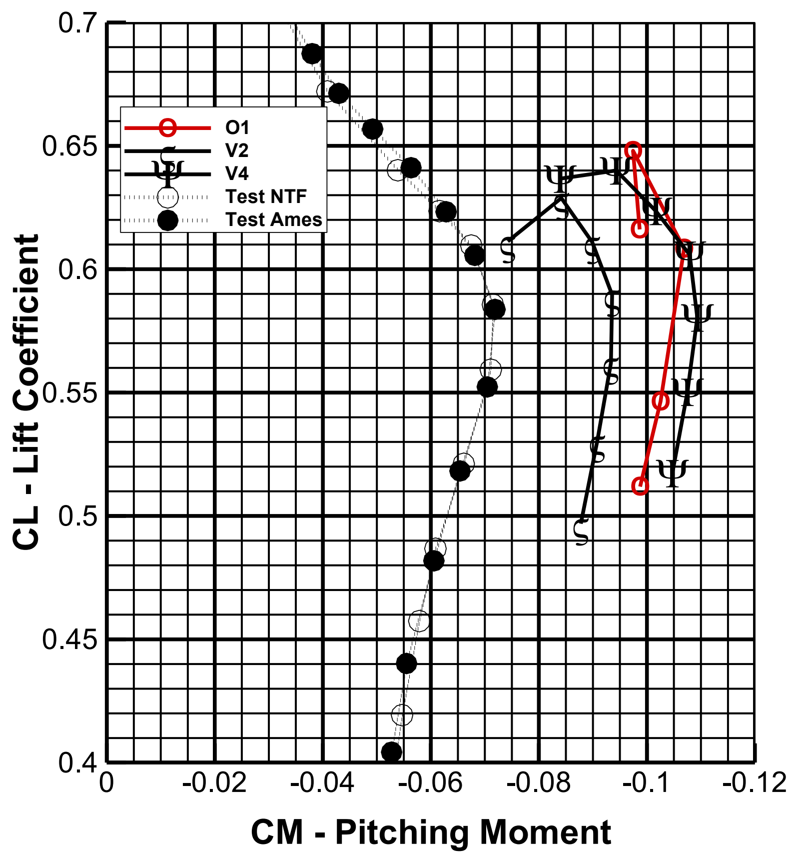
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Outliers - CL Break between AOA=3.50 and 3.75
Turbulence Model



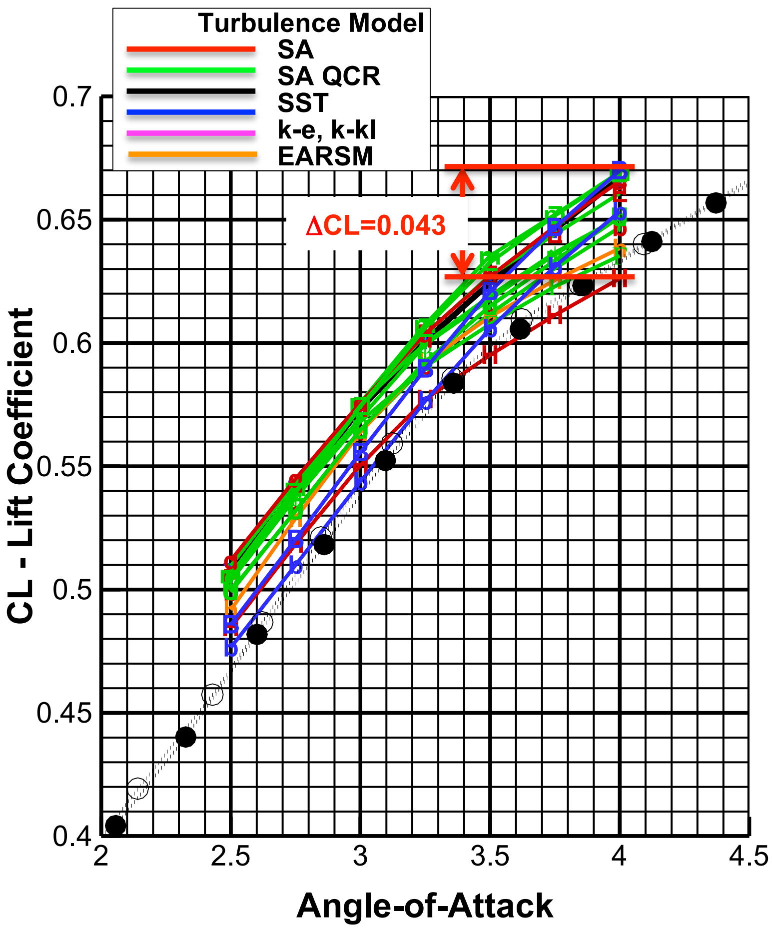


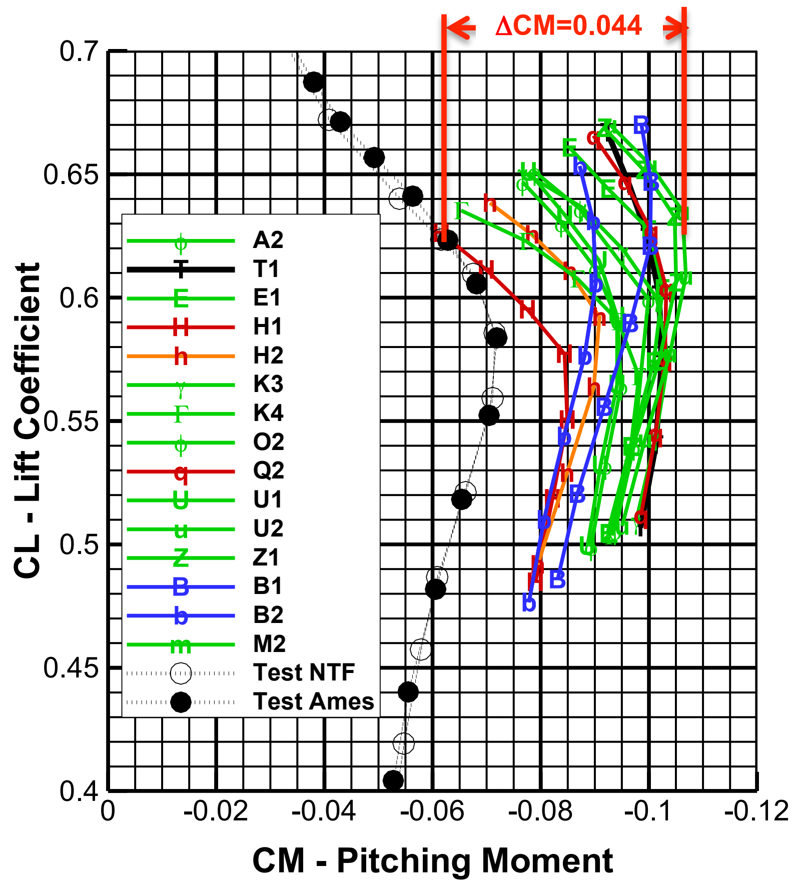
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Outliers - CL Break between AOA=3.75 and 4.00
Turbulence Model



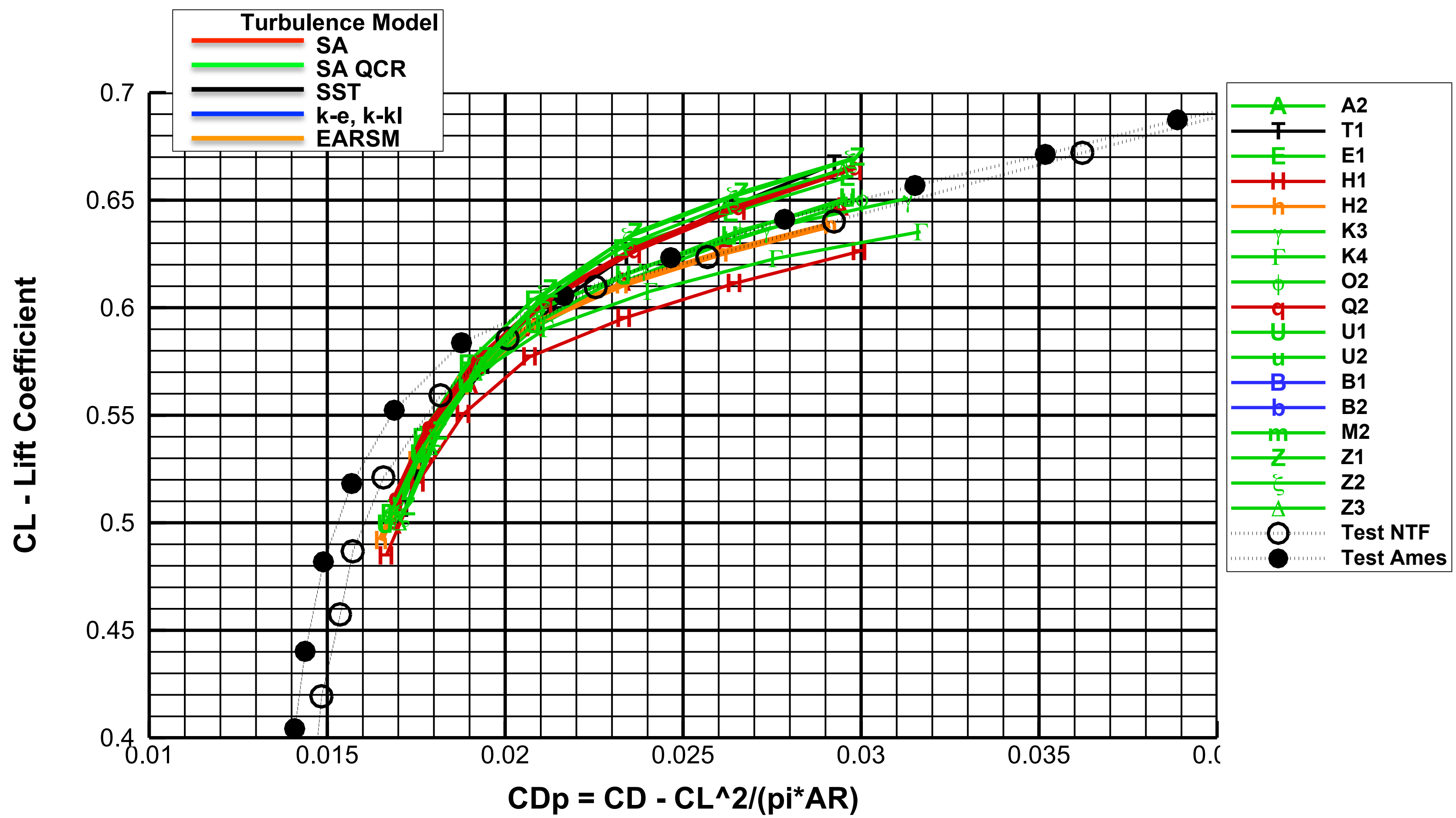


Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Solutions minus All Outliers
Turbulence Model Type





Case 3: Drag minus Idealized Induced Drag
Wing-Body w/Static Aeroelastics
Solutions minus All Outliers
Turbulence Model Type



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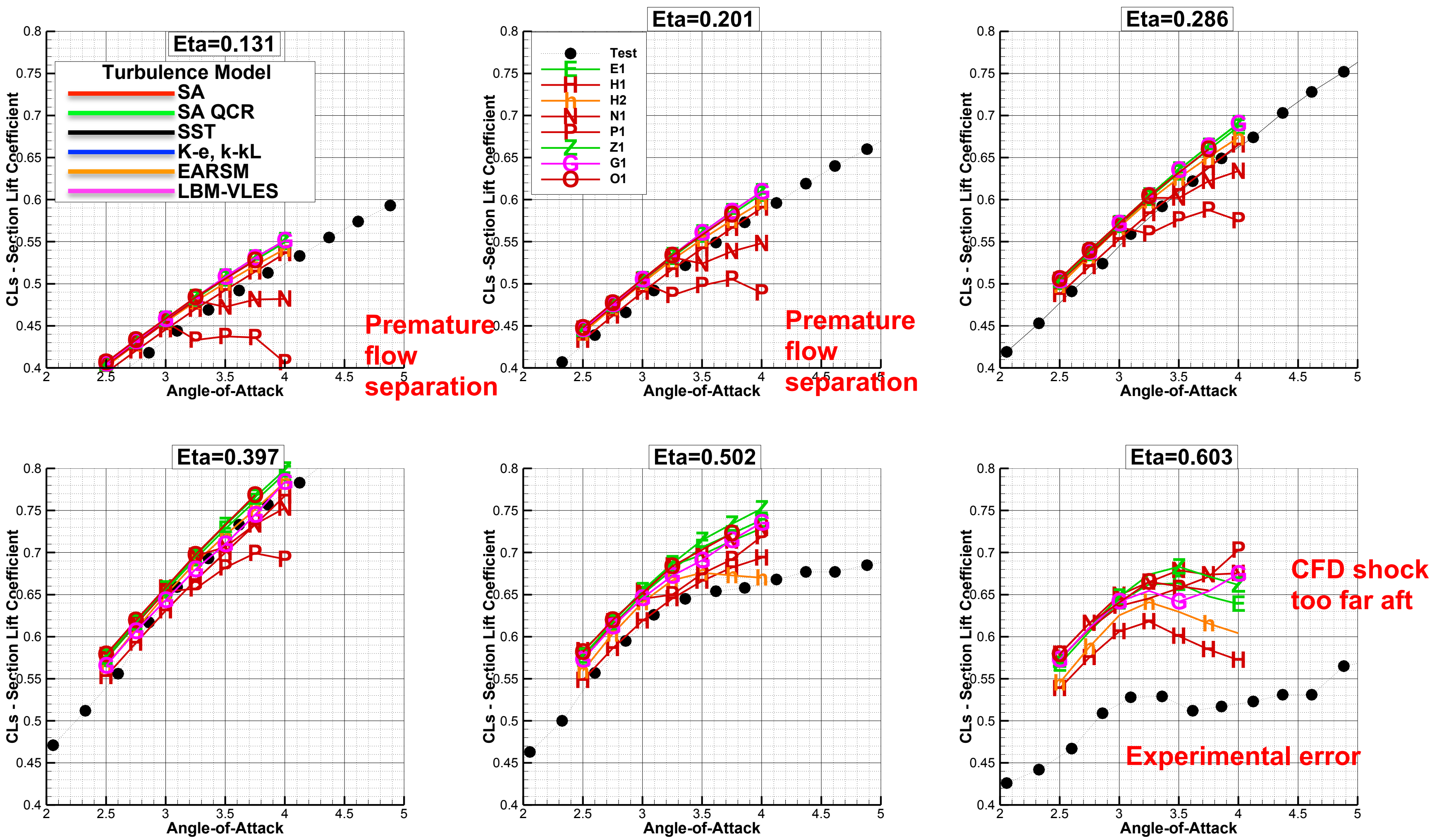
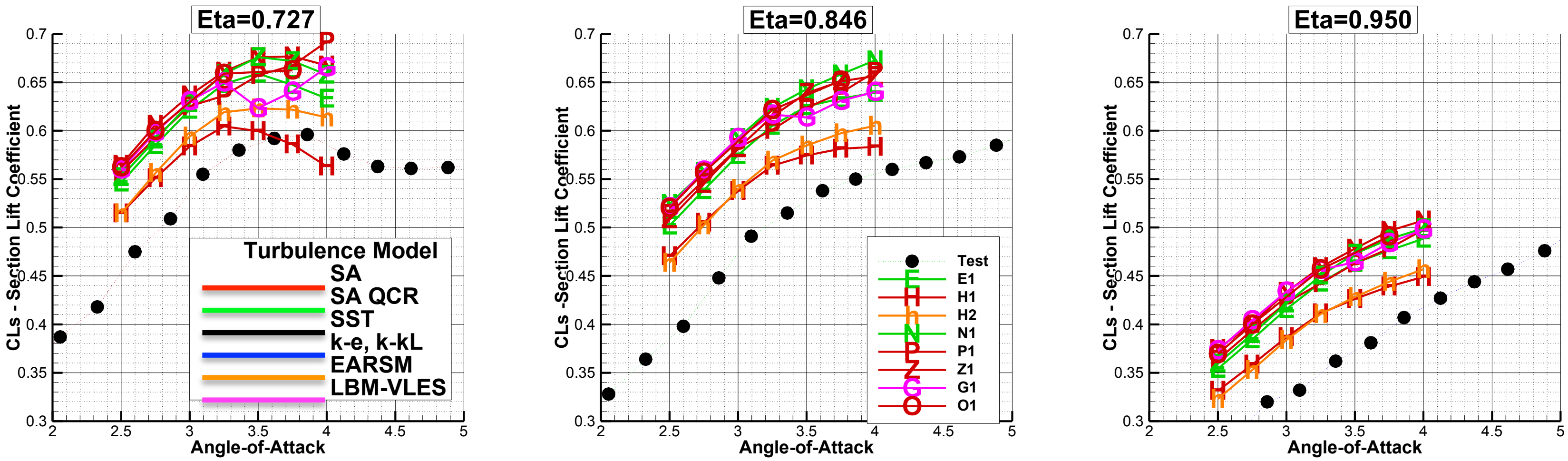
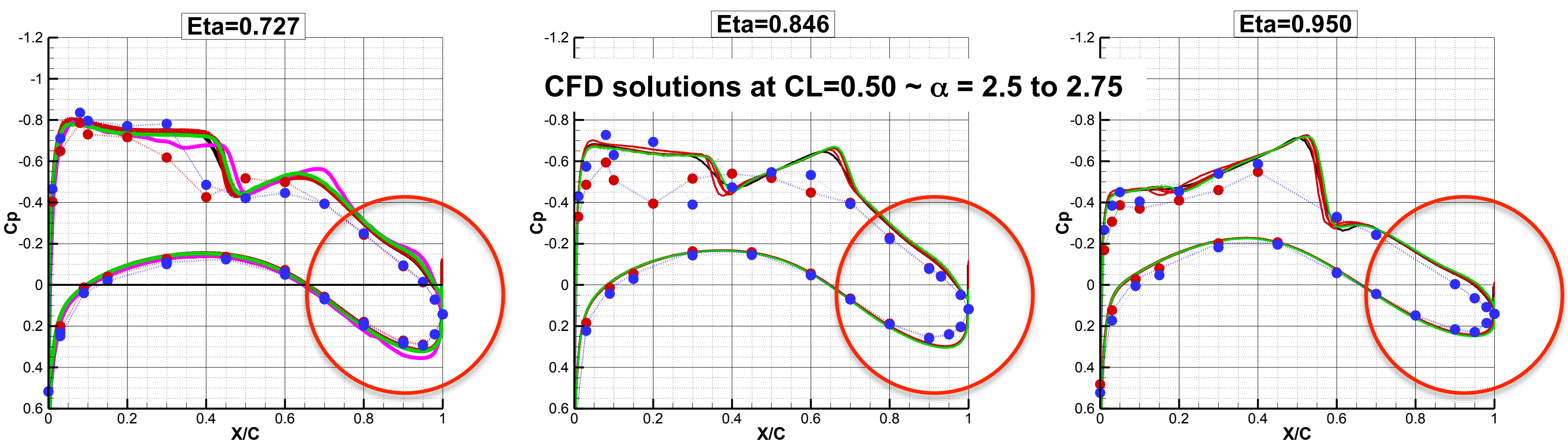
Case 3: Wing-Body Section Lift Coefficient M=0.85



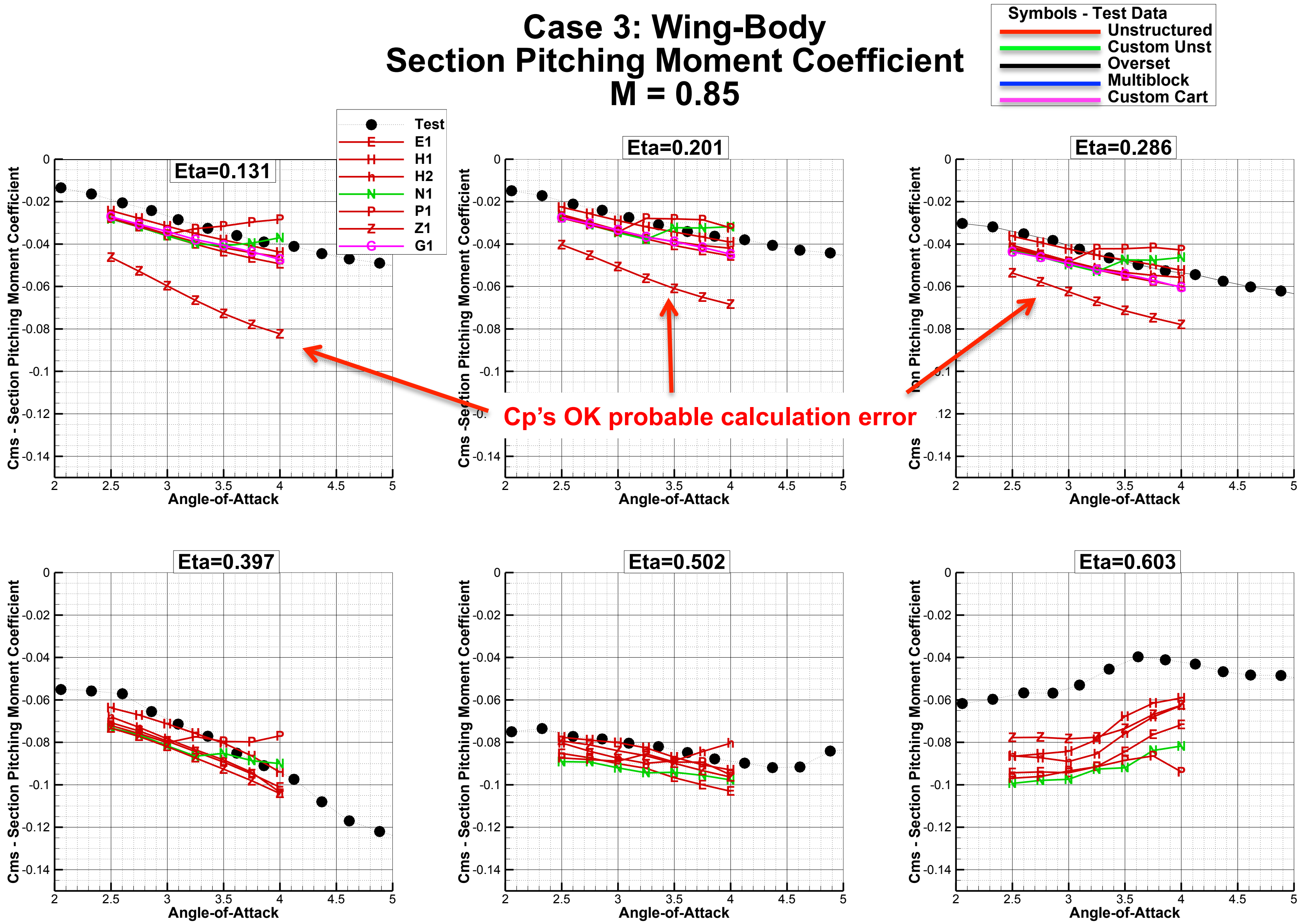
Case 3: Wing-Body
Section Lift Coefficient
M = 0.85



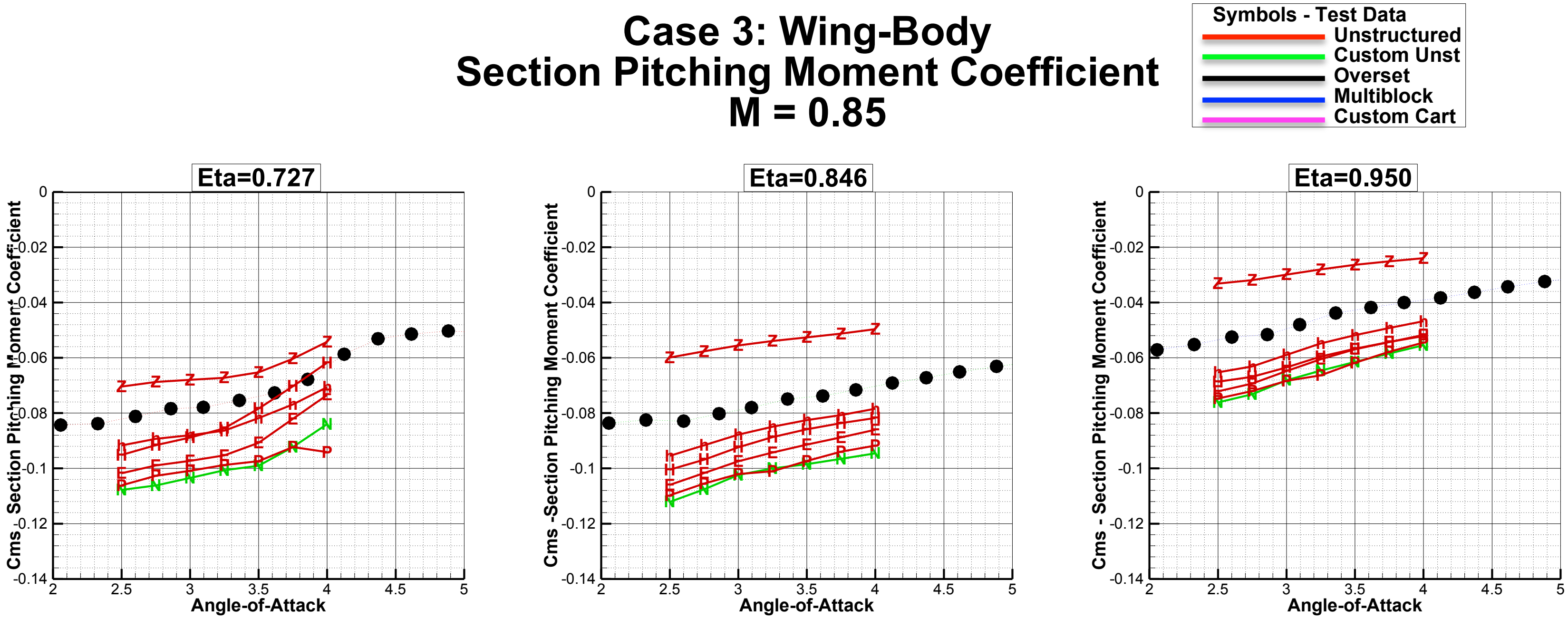
Excessive aft loading in CFD contributes to excessive lift and pitching moment outboard



Case 3: Wing-Body
Section Pitching Moment Coefficient
M = 0.85

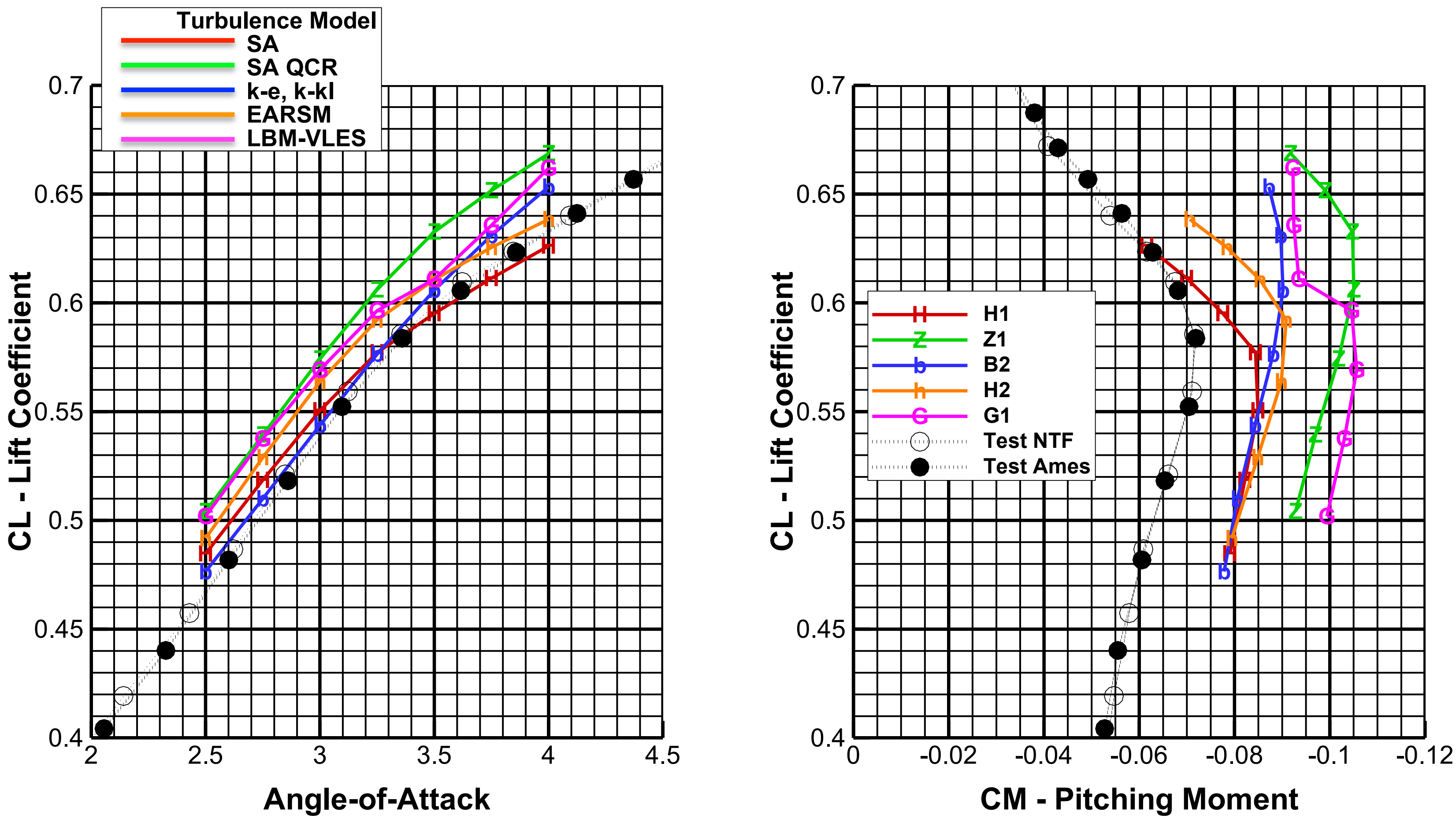


Case 3: Wing-Body
Section Pitching Moment Coefficient
M = 0.85

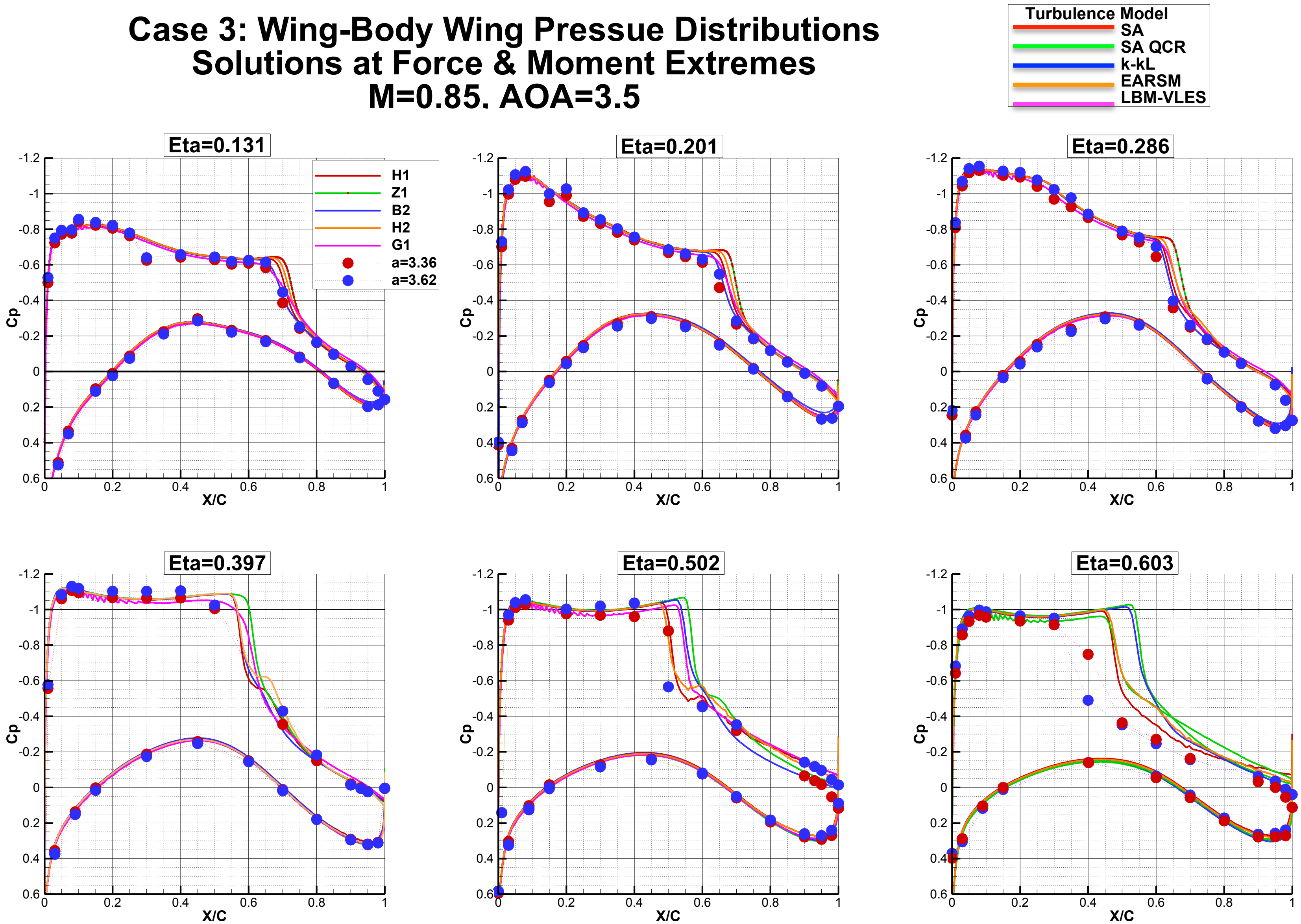


Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Solutions minus All Outliers* - Extremes
Turbulence Model Type

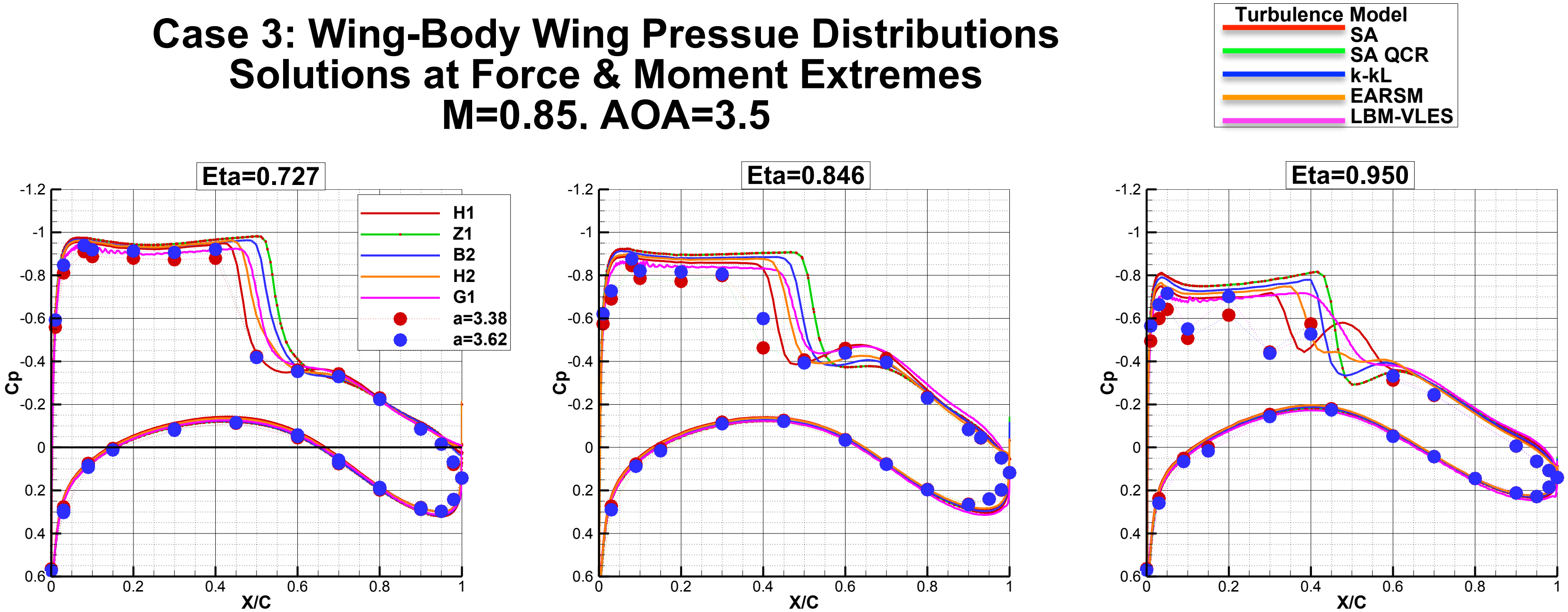
*G is considered an outlier



Case 3: Wing-Body Wing Pressue Distributions
Solutions at Force & Moment Extremes
M=0.85. AOA=3.5

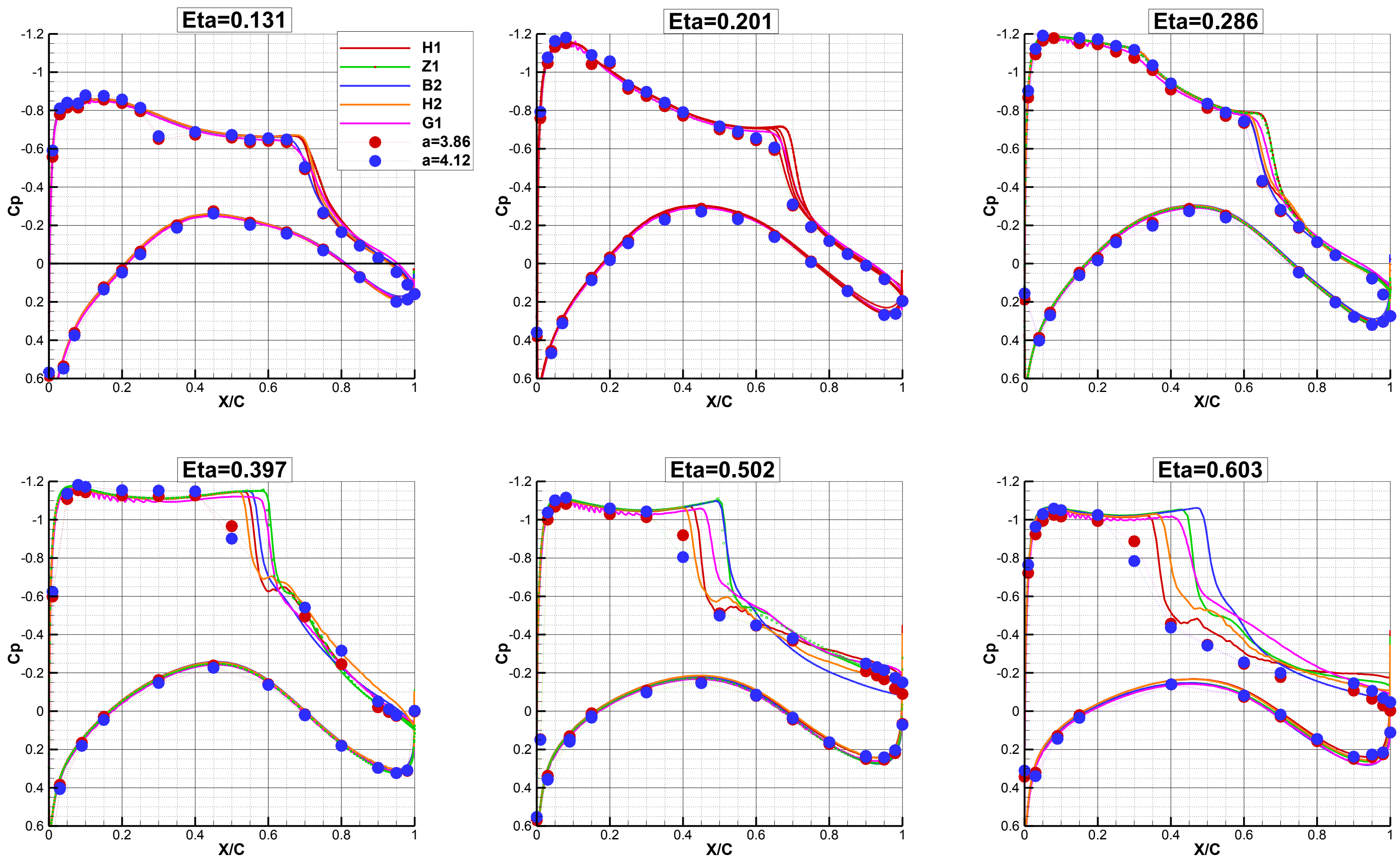


Case 3: Wing-Body Wing Pressue Distributions Solutions at Force & Moment Extremes M=0.85. AOA=3.5



Case 3: Wing-Body Wing Pressue Distributions
Solutions at Force & Moment Extremes
M=0.85. AOA=4.00

Turbulence Model
SA
SA QCR
k-kL
EARSM
LBM-VLES



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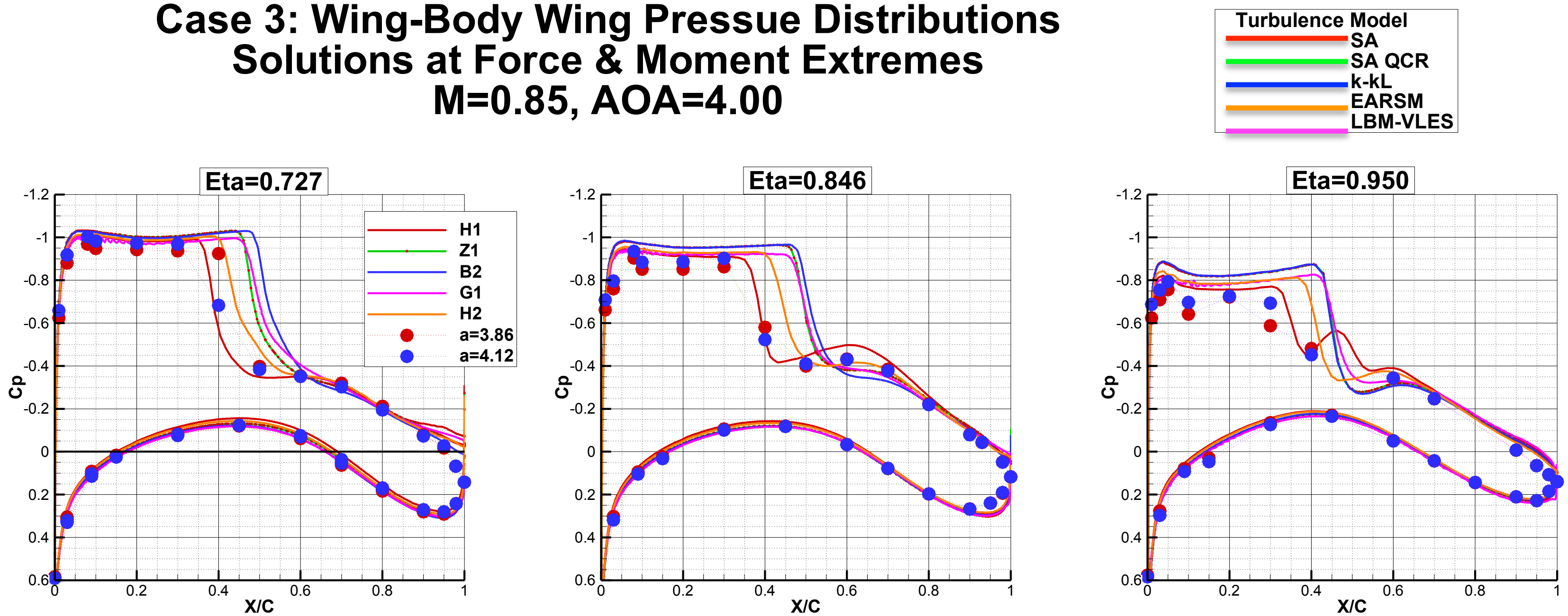
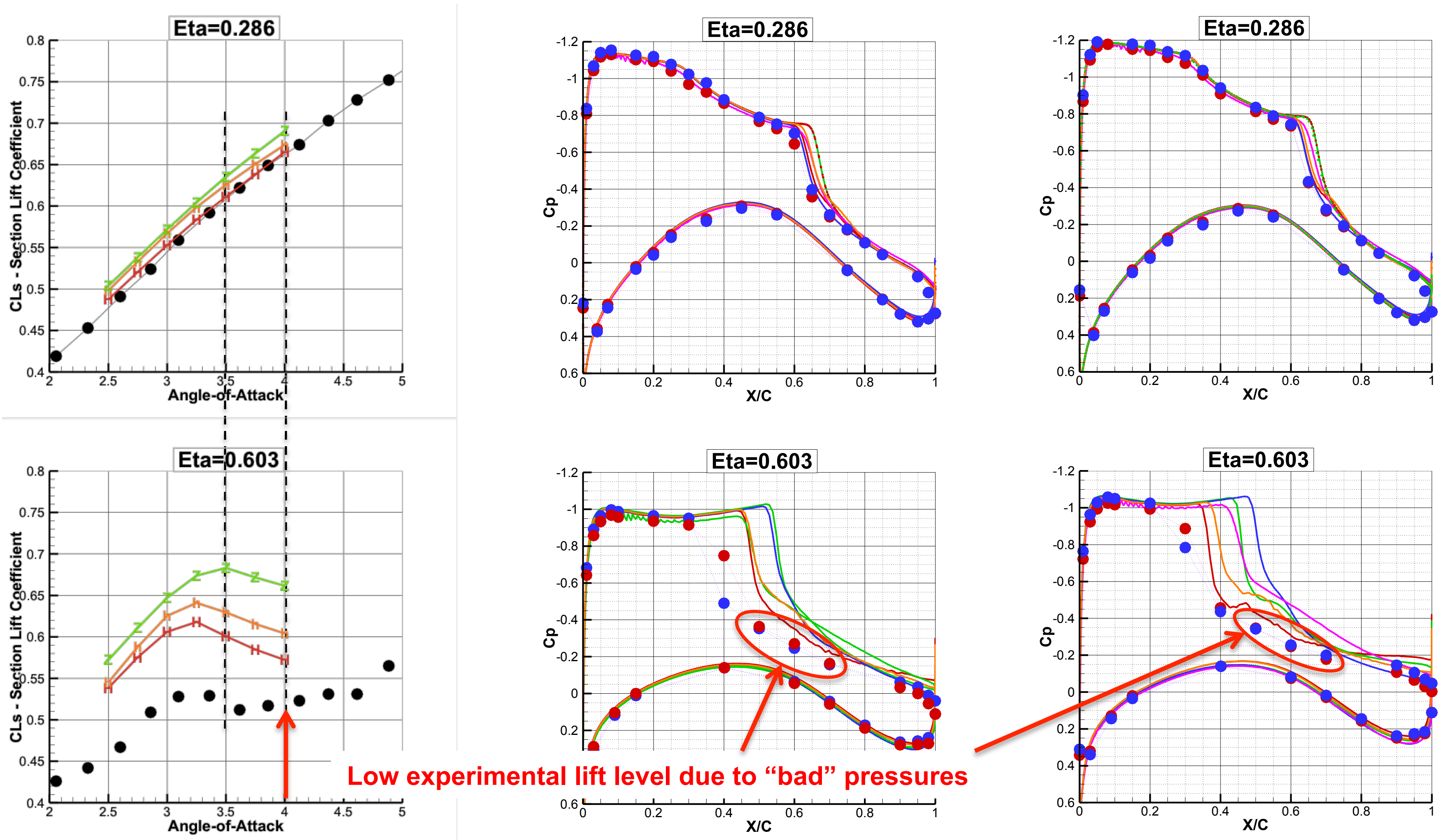
Case 3: Wing-Body Wing Pressue Distributions
Solutions at Force & Moment Extremes
M=0.85, AOA=4.00



Section Lift Coefficient α = 3.50 α = 4.00



Case 3 - Observations

- No clear break-outs with grid type or turbulence model (except for some outliers)
- In general, the k-e Lam-Bremhorst and LBM-VLES results tend outside the norm of the other solutions but this could have been due to grid/solution type.
- For all solutions minus outliers
  - Tighter forces and moment at α=2.5°
  - Significant force and moment spread at α=4.0° ΔCL=0.043, ΔCM=0.044
- Excessive aft-loading on outboard wing sections contributes to too negative section pitching moments and excessive section lift.
- Steady aeroelastic effects are significant
  - Inclusion greatly improved agreement with wind tunnel
- High angles of attack characterized by significant shock induced separation
  - How steady is the real flow at these conditions? Need dynamic test data?
  - If there is a significant amount of flow unsteadiness at high angles of attack is RANS adequate or do we need URANS or DES?

Outline:

- Participant Data
- Case 2: CRM Nacelle-Pylon Drag Increment
- Case 3: CRM WB Static Aero-Elastic Effect
- Case 4: CRM WB Grid Adaptation
- Case 5: CRM WB Coupled Aero-Structural Simulation
- Separation
- Observations/Issues

Case 4: CRM WB Grid Adaptation:

- NASA Common Research Model, Wing-Body
- Mach=0.85, C_L=0.500±0.001
- Chord Reynolds Number: 5×10^6
- Solution Adapted Grid

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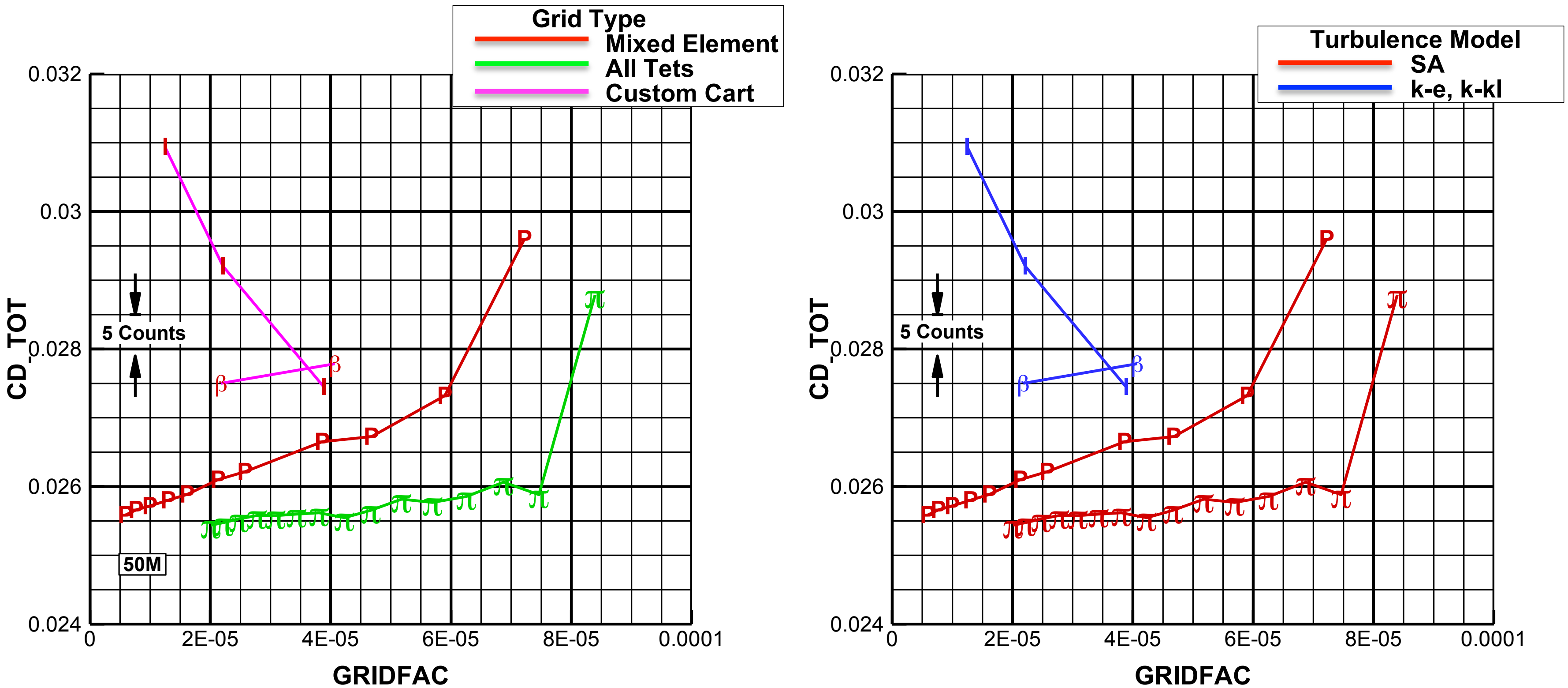
Case 4: CD_TOT - WB Grid Adaption
All Solutions by Grid Type and Turbulence Model



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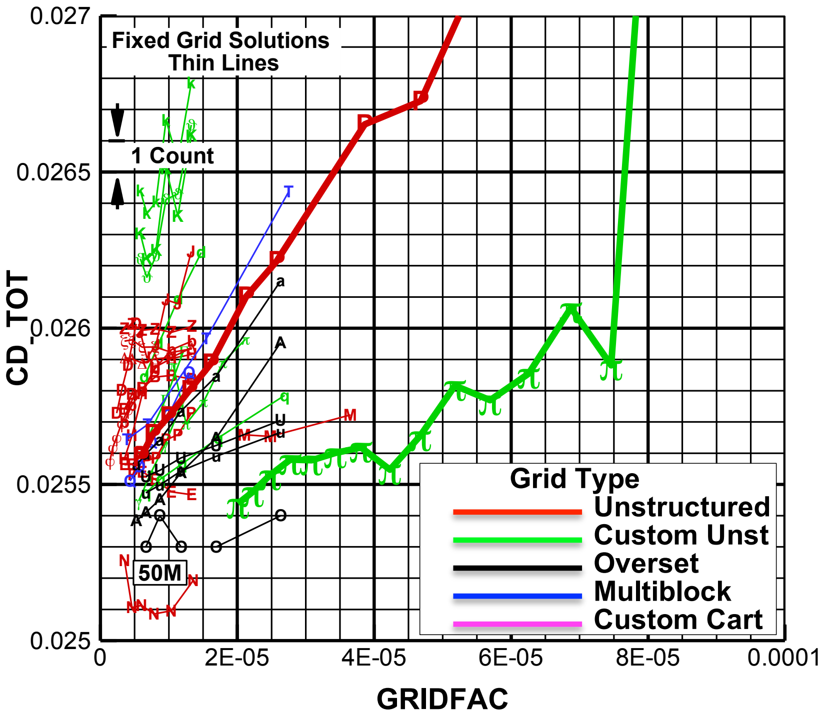
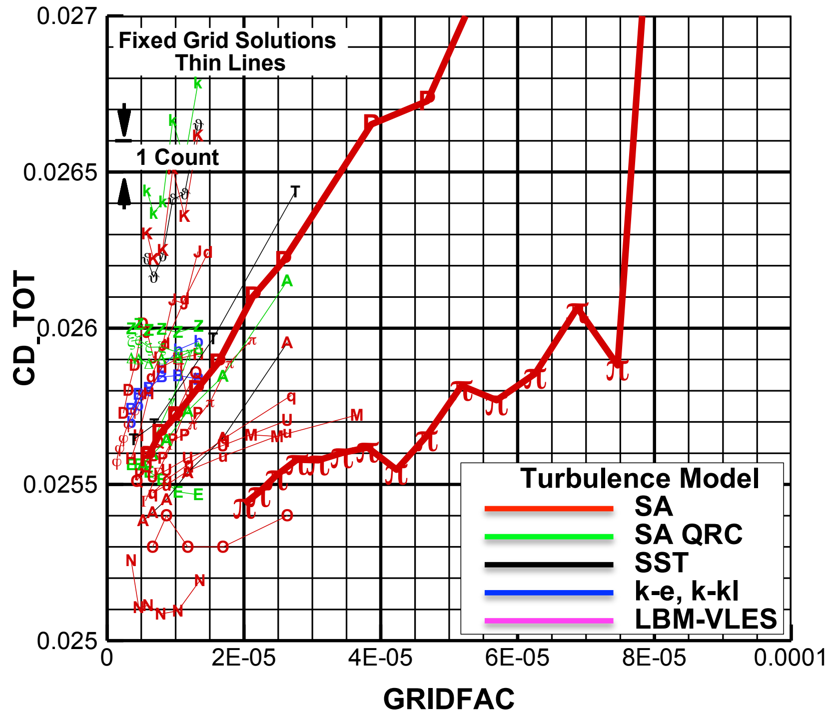
Case 4: CD_TOT - Wing-Body Grid Adaption
All Solutions by Grid Type and Turbulence Model





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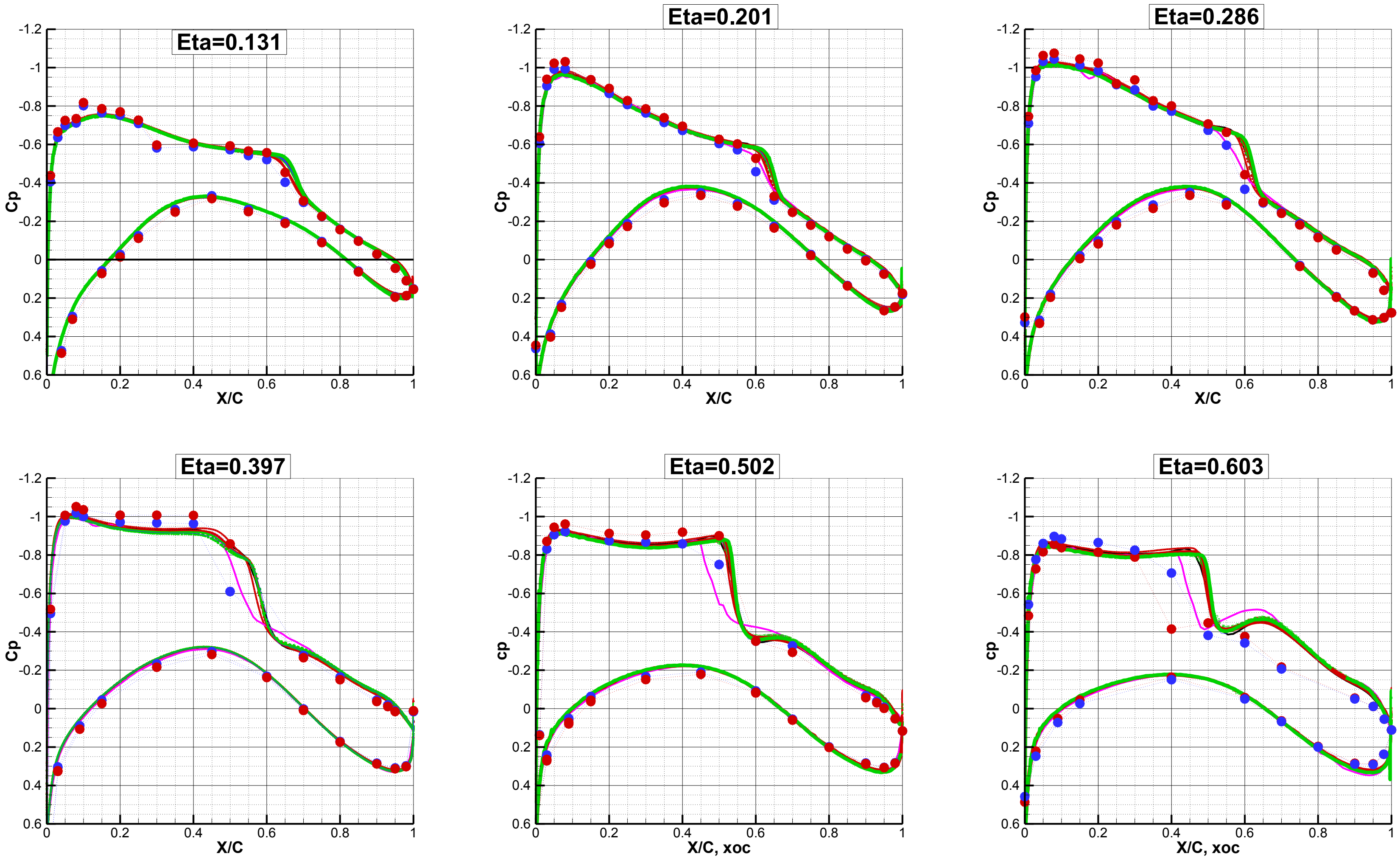
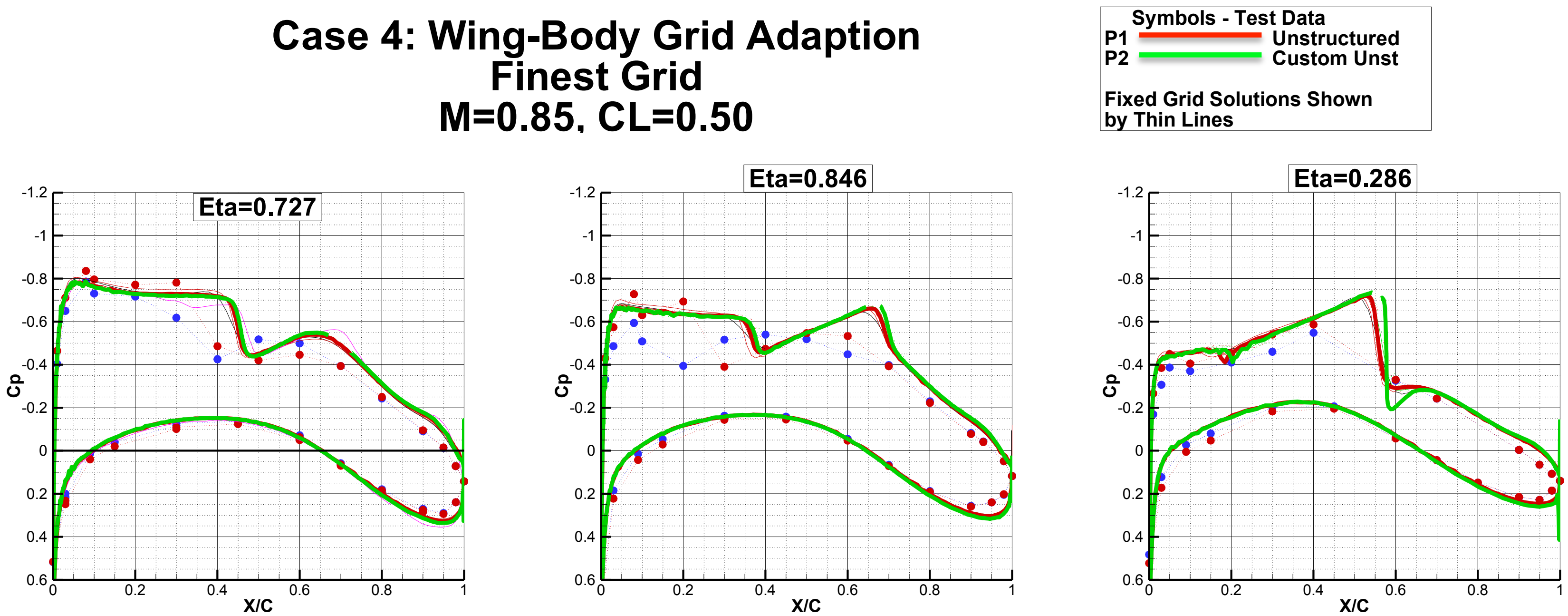
Case 4: Wing-Body Grid Adaption Finest Grid M=0.85, CL=0.50

Symbols - Test Data
P1 Unstructured
P2 Custom Unst

Fixed Grid Soluions Shown by Thin Lines



Case 4: Wing-Body Grid Adaption
Finest Grid
M=0.85, CL=0.50



Outline:

- Participant Data
- Case 2: CRM Nacelle-Pylon Drag Increment
- Case 3: CRM WB Static Aero-Elastic Effect
- Case 4: CRM WB Grid Adaptation
- Case 5: CRM WB Coupled Aero-Structural Simulation
- Separation
- Observations/Issues

Case 5: CRM WB Coupled Aero-Structural Simulation :

- NASA Common Research Model, Wing-Body
- Mach=0.85, C_L=0.500±0.001
- Chord Reynolds Number: $5x10^6$
- Fixed lift condition for the CRM Wing-Body coupled with computational structural analysis
- Medium Grid
- Structural FEM from the CRM Website

Outline:

- Participant Data
- Case 2: CRM Nacelle-Pylon Drag Increment
- Case 3: CRM WB Static Aero-Elastic Effect
- Case 4: CRM WB Grid Adaptation
- Case 5: CRM WB Coupled Aero-Structural Simulation
- Separation
- Observations/Issues

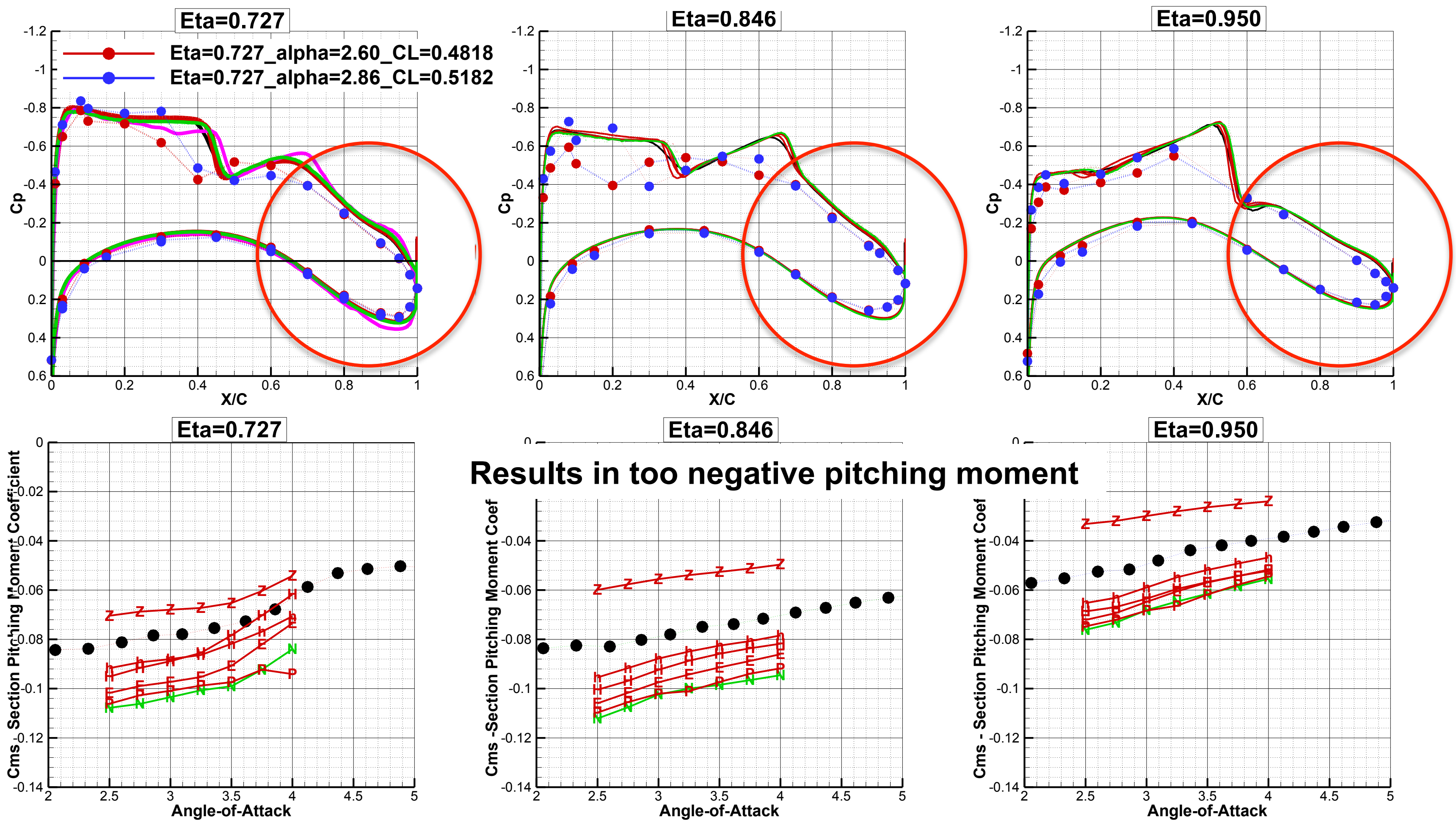
General Observations:

- Very successful workshop. **Thank You!**
  - 48 data submittals, many with parametric variations in grid type and/or turbulence model
- Still more variation than desired
  - Some improvement from DPW5: We are getting better
- Drag comparisons to wind tunnel generally favorable
  - Variations similar between WT and CFD
  - Very good on increment for nacelle-pylon
  - Aeroelastic effects essential to decent agreement with test data

General Observations (Cont'd):

- Force/Moment predictions better at α=2.5°
  - Less separation
  - Bigger spread at α=4.0°
- Pressures consistent with Force/Moments
  - Wide variation in α for shock separation for many cases
- Large variations in separation prediction
  - Premature flow separation is still an issue for many solutions
  - SOB Separation
  - TE Separation and Buffet onset alpha
  - Is RANS good enough? Is flow steady?

Issues: Excessive Aft Loading
Wing-Body
Mach=0.85, CL=0.50



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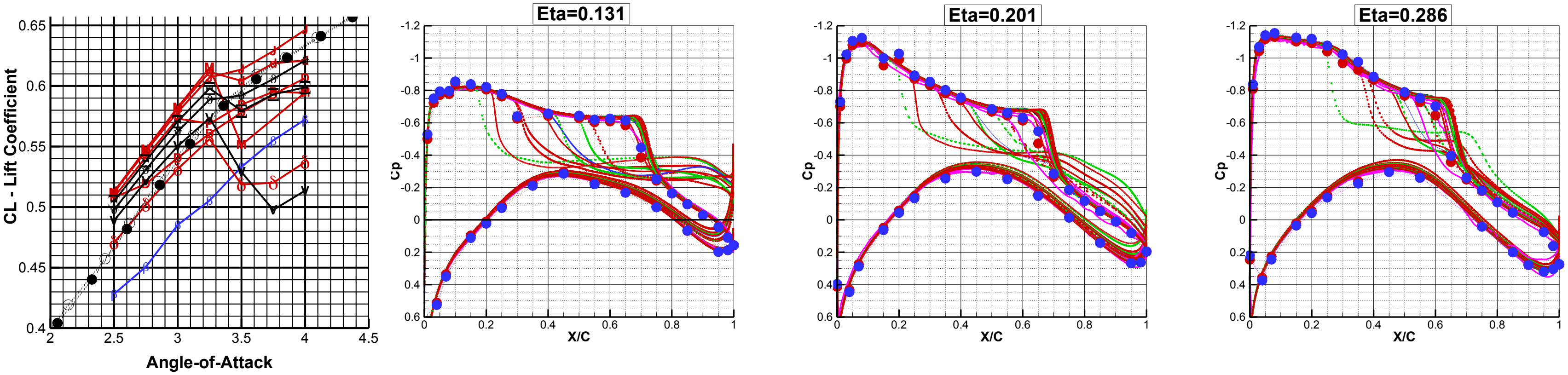
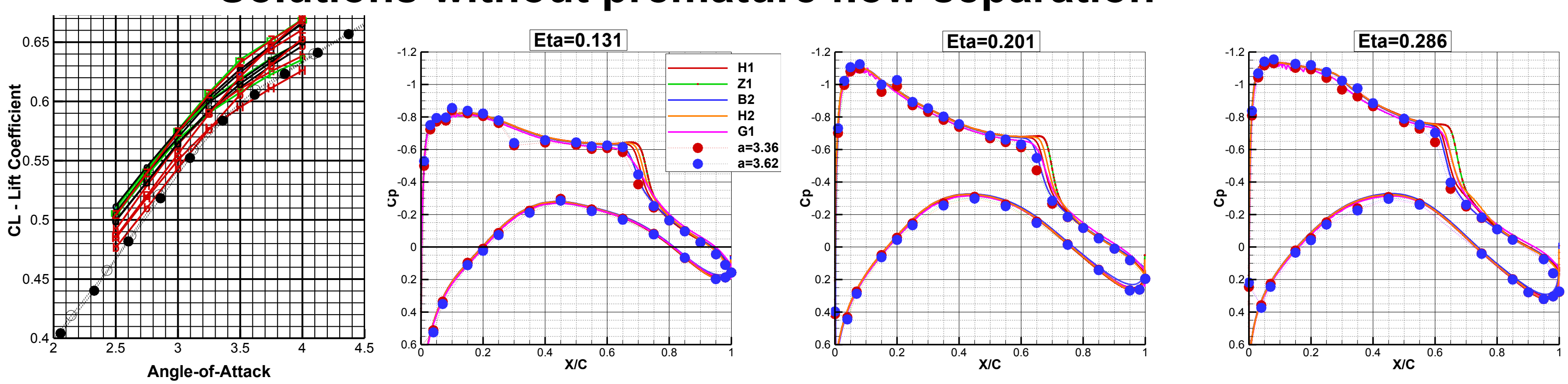
Issues: Premature Flow Separation

Case 3: Wing-Body
Mach=0.85, AOA=3.50

Many solutions showed premature flow separation



Solutions without premature flow separation



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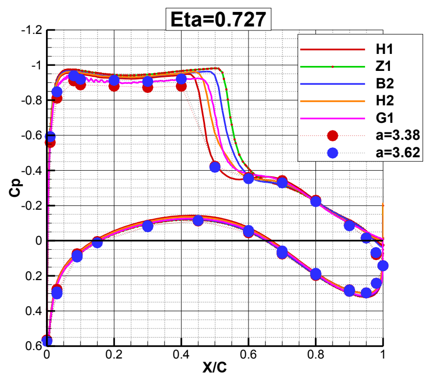
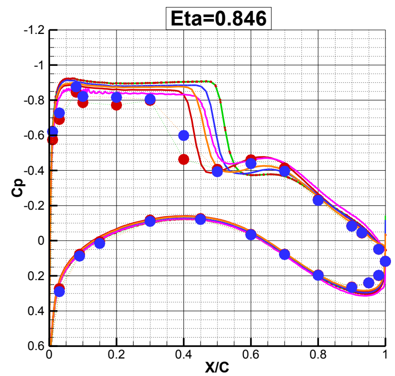
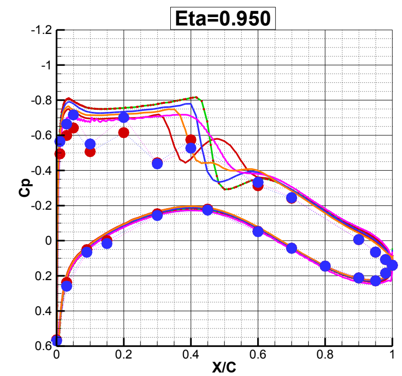
Issues: Aft Shock Location

Case 3: Wing-Body
Mach=0.85,

AOA=3.50

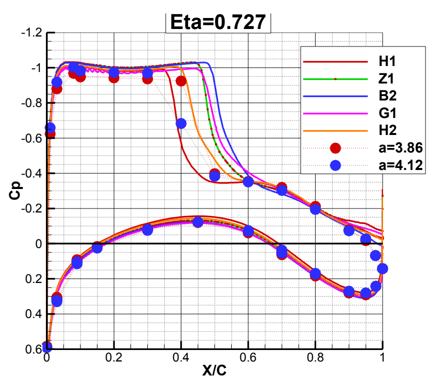


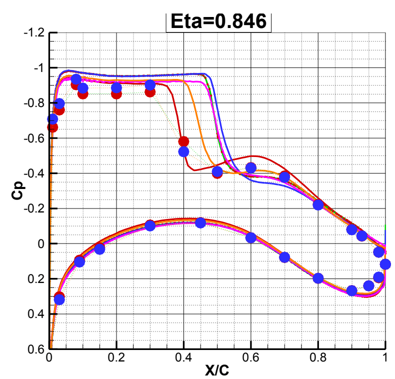


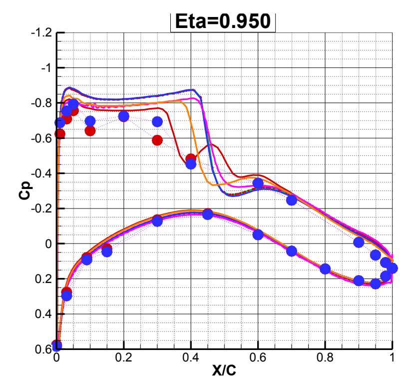


Shock location too far aft for most solutions

AOA=4.00







We also need better experimental data that shows just how much the shock is moving at these flow conditions

Further Study:

- Include boundary layer transition model?
  - Forced/Free
- Unsteady RANS?
  - Will only help if flow is unsteady
- LES/DES?
  - DES only helps for off-body separation
  - LES (beyond current SOA?)