Is the Problem with the Mesh, the Turbulence Model, or the Solver?

Statistical Analysis of High Lift and Drag Prediction Workshop Data

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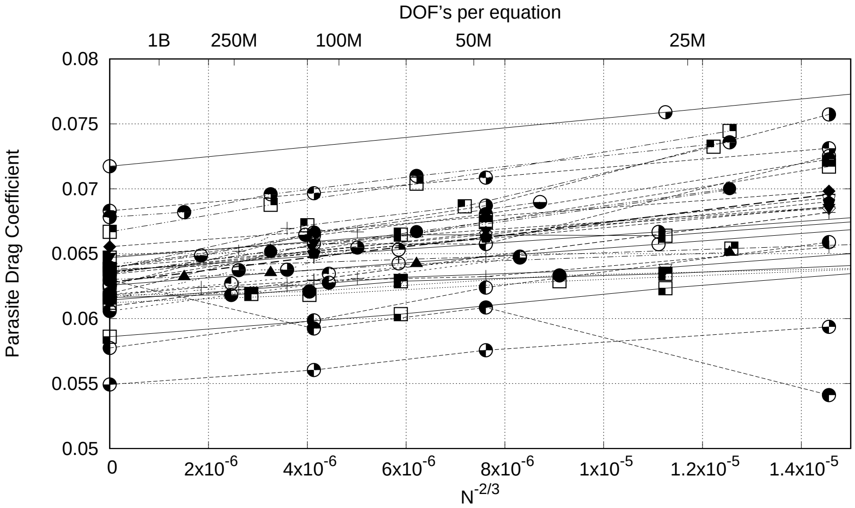
Motivation


DOF's per equation
1B
250M
100M
50M
25M
0.08
0.075
0.07
0.065
0.06
0.055
0.05
Parasite Drag Coefficient
0
2x10^-6
4x10^-6
6x10^-6
8x10^-6
1x10^-5
1.2x10^-5
1.4x10^-5
N^-2/3

Objectives

- Using statistical methods, try to determine the relative influence of
  - Mesh sequence
  - Turbulence model
  - Flow solver
  - User settings

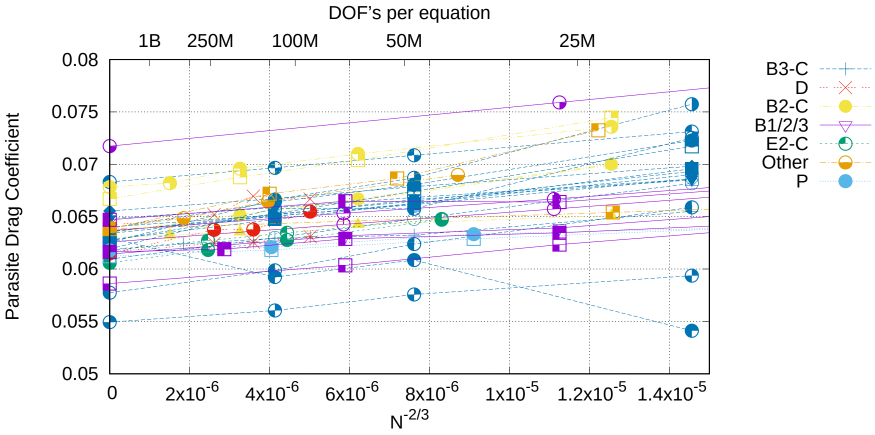
Approach

- Analyzed parasite drag, lift (HiLiftPW3 only), pitching moment
- Treated the data as having three independent variables: mesh set, turbulence model, flow solver
- Grouped data so that two of these three variables matched; not all datasets in all comparisons
  - Group = datasets that used (e.g.) Star-CCM+ and Spalart-Allmaras with different meshes
  - Subset = all groups that had the same solver and model: Star-CCM+/SA, Dragon/Wilcox88, PHASTA/SA, etc
- Compared variation within groups to total for the subset
  - Used sum of squares of difference (SSE) from group mean
  - What fraction of subset SSE comes from group SSE's?

Data Used: HiLiftPW3

- High-lift CRM test case at $\alpha = 8^\circ$, trying to avoid the worst of the stall-related uncertainties
- Analyzed 39 second-order unstructured mesh results that share a mesh sequence, a turbulence model or a flow solver with another result.
  - Eleven mesh sequences. Eight used more than once: five committee mesh variants, plus Oxford, Boeing, and DLR meshes.
  - Ten turbulence model variants. Seven used more than once: BSL, SA (four variants), SST, and Wilcox $k - \omega$.
  - Nineteen flow solvers. Eleven used more than once: CFD++, Dragon, Fluent, FUN3D, Kestrel, LOGOS, PHASTA, Star-CCM+, SU2, TAS, TAU.

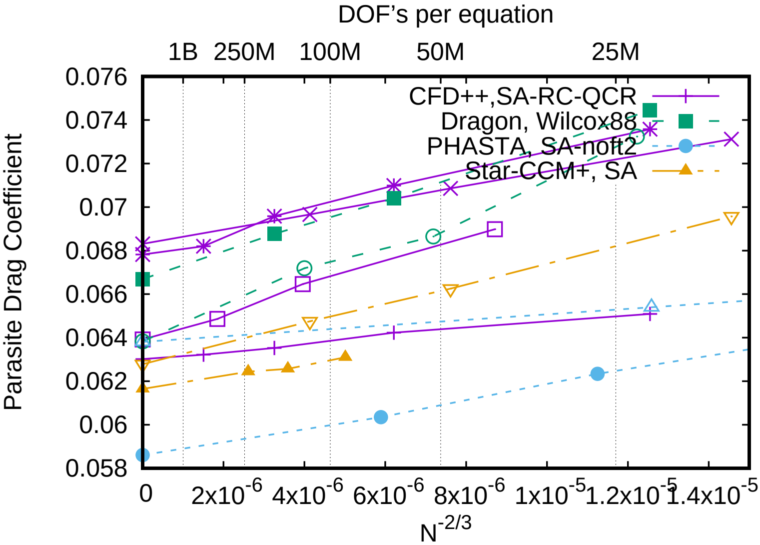
Overall Behavior: Drag



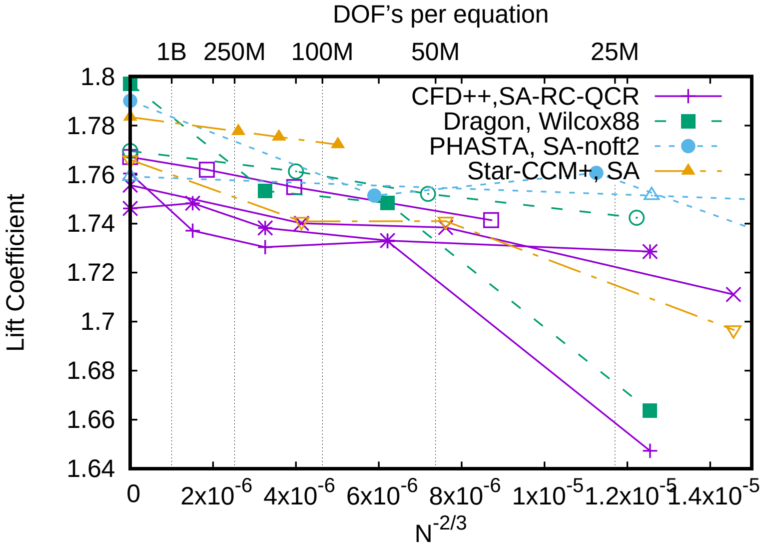
Comparison Groups: Mesh Variation

PID	Turb Model	Solver	Mesh
2.2	SA	Star-CCM+	D
3.2			B3-C
19.3	SA-RC-QCR	CFD++	B2-C
19.2			B2-C
6.1			B3-C
19.4			R
30.1	Wilcox88	Dragon	B2-C
30.2			F
35.1	SA-noft2	PHASTA	B1
35.3			M

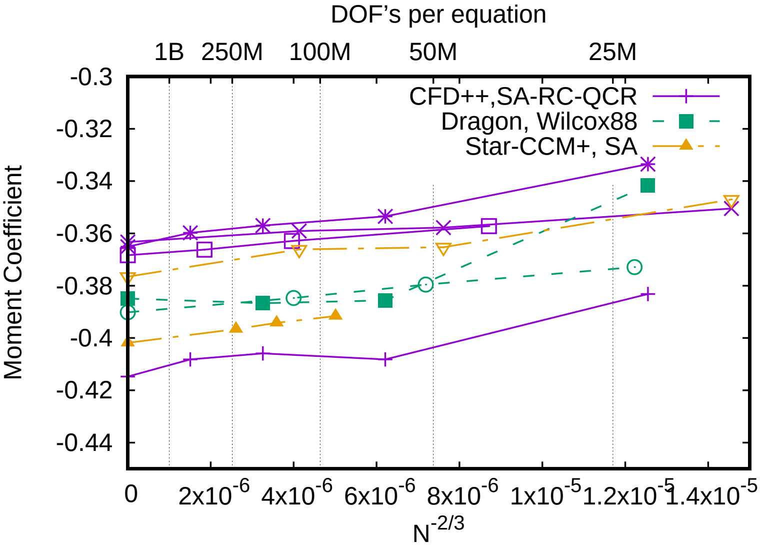
Parasite Drag Convergence: Mesh Variation



Lift Convergence: Mesh Variation



Moment Convergence: Mesh Variation



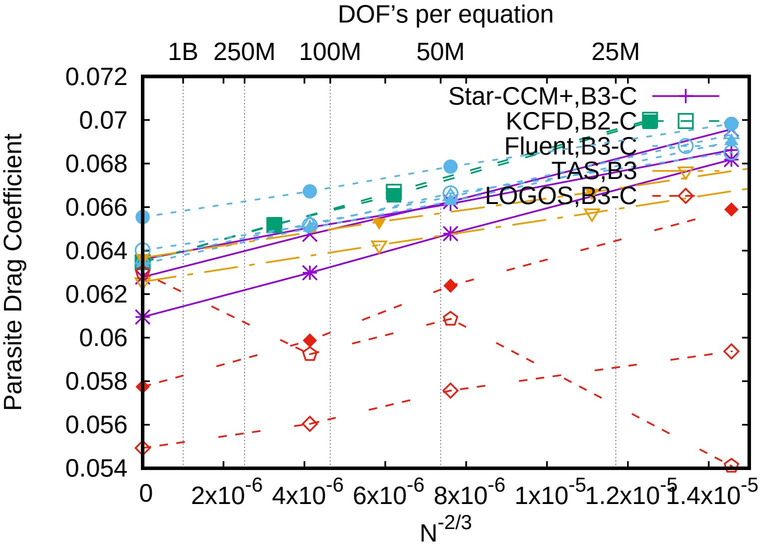
Statistical Results: Mesh Variation

Turb Model	Solver	C_L		$C_{D,para}$		C_M	
		Mean	SSE	Mean	SSE	Mean	SSE
SA	Star-CCM+	1.7747	$1.509 \cdot 10^{-4}$	0.0622	$6.430 \cdot 10^{-7}$	-0.3892	$3.203 \cdot 10^{-4}$
SA-RC-QCR	CFD++	1.7574	$2.328 \cdot 10^{-4}$	0.0658	$2.166 \cdot 10^{-5}$	-0.3779	$1.827 \cdot 10^{-3}$
Wilcox88	Dragon	1.7833	$3.754 \cdot 10^{-4}$	0.0653	$4.096 \cdot 10^{-6}$	-0.3876	$1.399 \cdot 10^{-5}$
SA-noft2	PHASTA	1.7747	$4.774 \cdot 10^{-4}$	0.0612	$1.353 \cdot 10^{-5}$	—	—
Overall		1.7695	$2.313 \cdot 10^{-3}$	0.0640	$7.749 \cdot 10^{-5}$	-0.3831	$2.384 \cdot 10^{-3}$
Within groups		—	53.5%	—	51.5%	—	90.7%

Comparison Groups: Model Variation

PID	Turb Model	Solver	Mesh
3.1	SST	Star-CCM+	B3-C
3.2	SA		
3.3	$k-\epsilon$ lagEB		
4.5	BSL	Kestrel	B2-C
4.6	SA		
10.1	SA	Fluent	B3-C
10.2	SST		
10.3	SST ($a_1 = 1$)		
10.4	BSL		
14.1	SA-noft2-R	TAS	B3
14.2	SA-noft2-R-QCR2000		
16.1	RSM-SSG/LLR-w	LOGOS	B3-C
16.2	SA		
16.3	SST		

Parasite Drag Convergence: Model Variation



Statistical Results: Model Variation

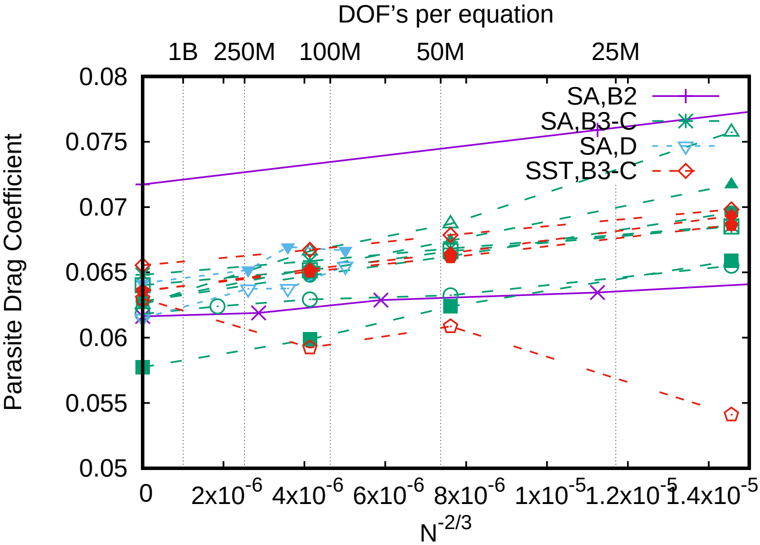
Mesh Set	Solver	C_L		$C_{D,para}$		C_M	
		Mean	SSE	Mean	SSE	Mean	SSE
B2-C	Kestrel/KCFD	1.7921	$1.565 \cdot 10^{-4}$	0.0635	$1.800 \cdot 10^{-11}$	—	—
B3-C	Star-CCM+	1.7862	$3.142 \cdot 10^{-3}$	0.0624	$3.677 \cdot 10^{-6}$	-0.3975	$2.396 \cdot 10^{-3}$
B3-C	Fluent	1.7486	$1.363 \cdot 10^{-3}$	0.0641	$2.867 \cdot 10^{-6}$	-0.3663	$1.071 \cdot 10^{-3}$
B3-C	LOGOS	1.8283	$8.000 \cdot 10^{-3}$	0.0586	$3.338 \cdot 10^{-5}$	-0.4473	$3.871 \cdot 10^{-3}$
B3	TAS	1.7621	$2.190 \cdot 10^{-4}$	0.0631	$6.050 \cdot 10^{-7}$	-0.3649	$2.574 \cdot 10^{-4}$
	Overall	1.7819	$2.484 \cdot 10^{-2}$	0.0623	$1.001 \cdot 10^{-4}$	-0.3941	$2.091 \cdot 10^{-2}$
Within groups		—	51.9%	—	40.5%	—	36.3%

Comparison Groups: Code Variation

PID	Turb Model	Solver	Mesh
1.1	SA	Mflow	B3-C
3.2		Star-CCM+	
10.1		Fluent	
16.2		LOGOS	
19.1		SU2	
34.1		SU2	
2.1	SA	OpenFOAM	D
2.2		Star-CCM+	
21.1		BRU3D	
3.1	SST	Star-CCM+	B3-C
10.2		Fluent	
16.3		LOGOS	
18.1	SA	elsA	B2
39.1		FUN3D	

Summary

Parasite Drag Convergence: Code Variation



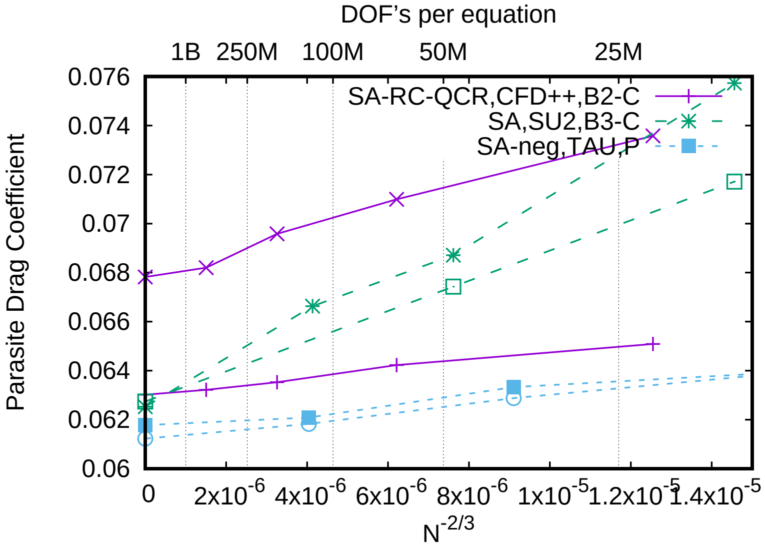
Statistical Results: Code Variation

Mesh Set	Turb Model	C_L		$C_{D,para}$		C_M	
		Mean	SSE	Mean	SSE	Mean	SSE
B2-C	SA	1.7963	$3.039 \cdot 10^{-3}$	0.0667	$5.107 \cdot 10^{-5}$	-0.3693	$2.245 \cdot 10^{-7}$
B3-C	SA	1.7925	$2.708 \cdot 10^{-2}$	0.0623	$3.069 \cdot 10^{-5}$	-0.3810	$2.387 \cdot 10^{-3}$
B3-C	SST	1.7603	$4.211 \cdot 10^{-3}$	0.0639	$3.746 \cdot 10^{-6}$	-0.3794	$3.861 \cdot 10^{-3}$
D	SA	1.7530	$7.087 \cdot 10^{-3}$	0.0624	$4.528 \cdot 10^{-6}$	-0.3962	$2.553 \cdot 10^{-4}$
Overall		1.7748	$4.667 \cdot 10^{-2}$	0.0635	$1.230 \cdot 10^{-4}$	-0.3829	$7.469 \cdot 10^{-3}$
Within groups		—	88.7%	—	73.2%	—	87.1%

Comparison Groups: User Variation

PID	Turb Model	Solver	Mesh
6.1 19.3	SA-RC-QCR	CFD++	B2-C
19.1 34.1	SA	SU2	B3-C
26.1 26.2	SA-neg	TAU	P

Parasite Drag Convergence: User Variation



Statistical Results: User Variation

Turb Model	Solver	Mesh Set	C_L		$C_{D,para}$		C_M	
			Mean	SSE	Mean	SSE	Mean	SSE
SA-RC-QCR	CFD++	B2-C	1.7533	$1.013 \cdot 10^{-4}$	0.0654	$1.153 \cdot 10^{-5}$	-0.3899	$1.233 \cdot 10^{-3}$
SA	SU2	B3-C	1.8576	$1.462 \cdot 10^{-2}$	0.0626	$2.205 \cdot 10^{-8}$	-0.3805	$3.65 \cdot 10^{-4}$
SA-neg	TAU	P	1.7769	$1.551 \cdot 10^{-5}$	0.0615	$1.529 \cdot 10^{-7}$	-0.3761	$2.592 \cdot 10^{-5}$
	Overall		1.7959	$2.670 \cdot 10^{-2}$	0.0632	$2.795 \cdot 10^{-5}$	-0.3822	$1.823 \cdot 10^{-3}$
	Within groups		—	55.2%	—	41.9%	—	89.0%

Summary of HiLiftPW3 Analysis

Fraction of Variation within Matched Groups

	C_L	$C_{D,para}$	C_M
Mesh	53.5%	51.5%	90.7%
Model	51.9%	40.5%	36.3%
Solver	86.8%	71.3%	87.8%
User	55.2%	41.9%	89.0%

Data Used: DPW5

- Fixed-lift grid-convergence test case.
- Committee-supplied meshes were as nearly identical in point locations as possible; variations also exclusively in connectivity.
- Analyzed 31 second-order unstructured mesh results that share a mesh sequence, a turbulence model or a flow solver with another result.
    - Seven mesh sequences. Five used more than once: three committee mesh variants, plus JAXA and Embraer meshes.
    - Seven turbulence model variants. Five used more than once: SA (four variants), SST (two variants), and $k - \epsilon - R_t$.
    - Eleven flow solvers. Nine used more than once: BCFD, CFD++, Edge, FaSTAR, Fluent, FUN3D, MFlow, TAU and UPACS.

Summary of DPW5 Analysis

Fraction of Variation within Matched Groups

	$C_{D,para}$	C_M
Mesh	40.8%	2.03%
Model	41.9%	60.3%
Solver	94.1%	9.6%
User	31.0%	1.4%

Conclusions

- Because the data is so sparse, firm conclusions are difficult to reach.
- DPW5 data shows less variation than HiLiftPW3 data.
    - DPW5 meshes were as nearly identical as feasible.
    - DPW5 flow condition is also less challenging.
- Mesh and turbulence model have about equally large effects.
- Implementation is at least as big a source of error as mesh or model.
- User choices matter: a confounding factor.

Acknowledgments

- Chris Rumsey (NASA Langley) provided access to the HiLiftPW3 data.
- Joe Morrison (NASA Langley) provided access to the DPW5 data.