

CFD Validation of a Hypersonic Cone-Slice-Flap Configuration

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with

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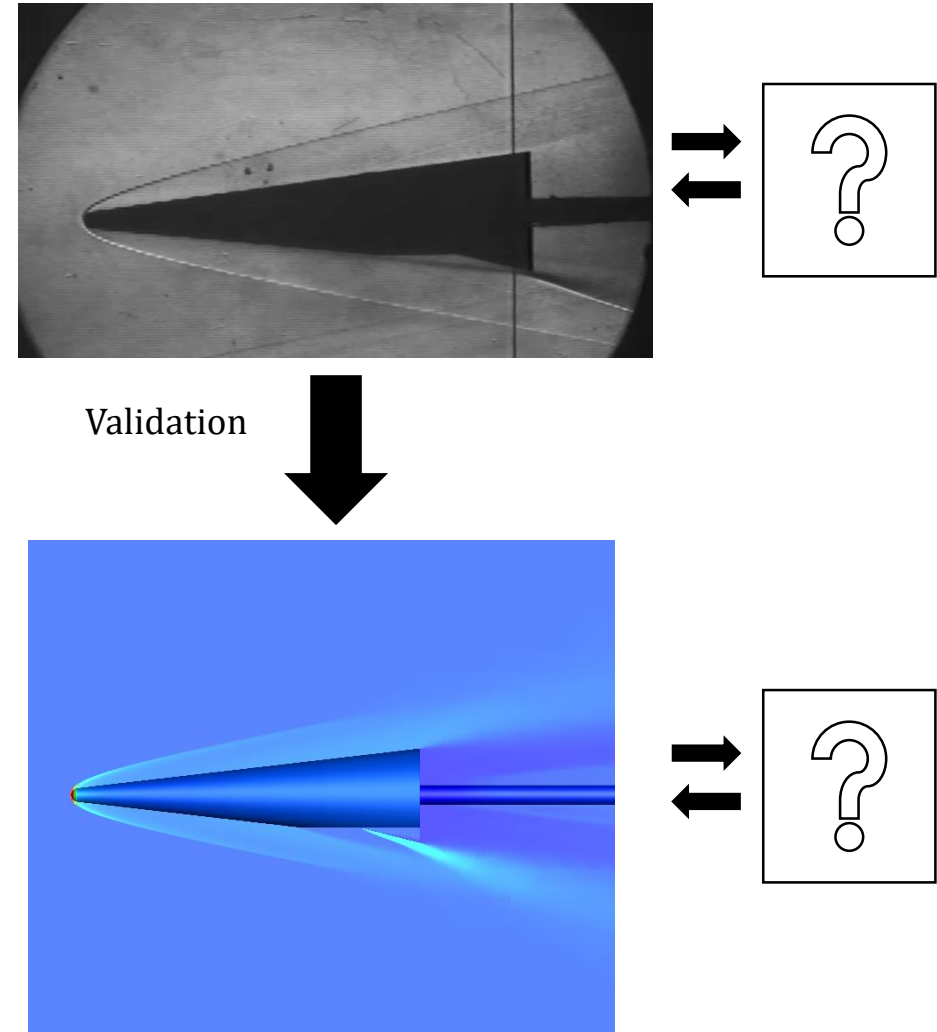
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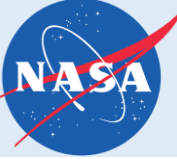
Introduction



- ❖ Model validation determines the degree of accuracy between the real world and the model
- ❖ This work focuses on quantifying model-form uncertainty through a validation approach that uses an area metric for lift, drag, and moment coefficient
- ❖ This area metric captures differences between experimental and simulation data with aleatory and epistemic uncertainty included in both sets of data



Experimental Setup and Uncertainty



Test conducted in the 20-inch Mach 6 Tunnel at NASA Langley

Flow Conditions

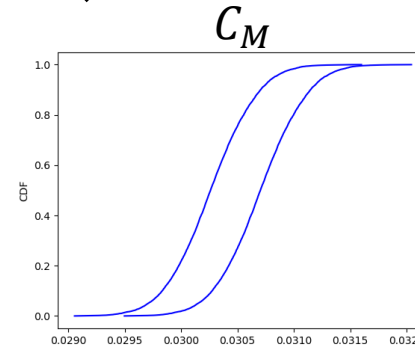
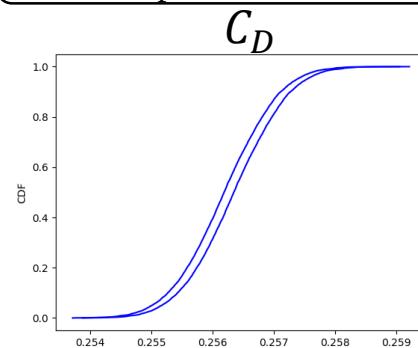
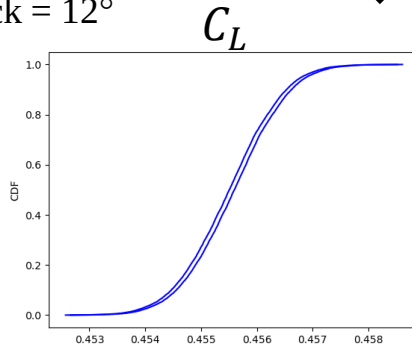
Run	Reynolds Number [1/ft]	Mach	AoA Range	Total pressure [psia]	Freestream Total temperature [R]	Freestream dynamic pressure [psia]
14	2,600,157	5.943	[0°,12°]	144.7	863.06	2.43

Systematic uncertainty – error due to measurement

	Uncertainty Variable	Classification	Uncertainty Type	Nominal	Uncertainty
Calibration uncertainty	AF (lbf)	aleatory	normal	AF (lbf) WT reading	0.01 (lbf) sd
	NF (lbf)	aleatory	normal	NF (lbf) WT reading	0.005 (lbf) sd
	PM (lbf)	aleatory	normal	PM (lbf) WT reading	0.0165 (lbf) sd
Settling chamber uncertainty	$p_{T_{\infty}}$ (psia)	aleatory	normal	$p_{T_{\infty}}$ (psia) WT reading	0.1 (psia) sd
ESP module uncertainty	p_{nose} (psia)	aleatory	normal	p_{nose} (psia) WT reading	0.0075 (psia) sd
Distance measurement uncertainty	x_{tran} (in.)	epistemic	interval	0.2535 (in.)	+0.001 (in.)
	z_{tran} (in.)	epistemic	interval	0 (in.)	±0.001 (in.)
Pitch encoder uncertainty	α (deg)	epistemic	interval	α (deg) WT reading	±0.01 (deg)

Calorically perfect gas,
Isentropic flow relations

Angle of attack = 12°



Random error

- ❖ Error due to inherent changes in the WT experiment between runs

$$s_X = \frac{X_{max} - X_{min}}{2.059}$$

Angle of attack = 12°

Run	C_D	C_L	C_M	Uncertainty
14	0.2558	0.4547	0.0303	$U_{C_D} = 0.0008, U_{C_L} = 0.0010,$ $U_{C_M} = 0.0003$
29	0.2554	0.4537	0.0296	
52	0.2561	0.4536	0.0297	
76	0.2570	0.4557	0.0298	



Simulation Setup and Uncertainty

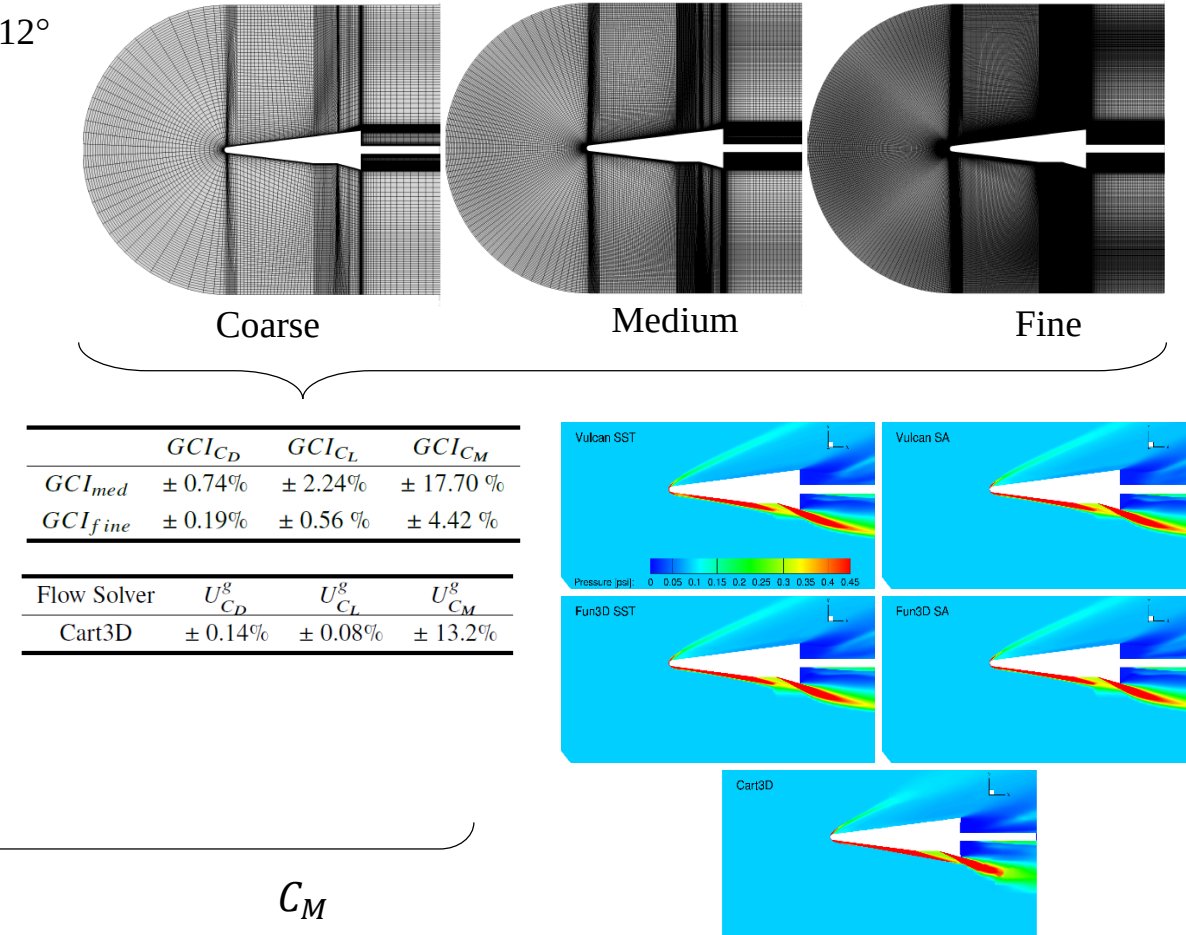
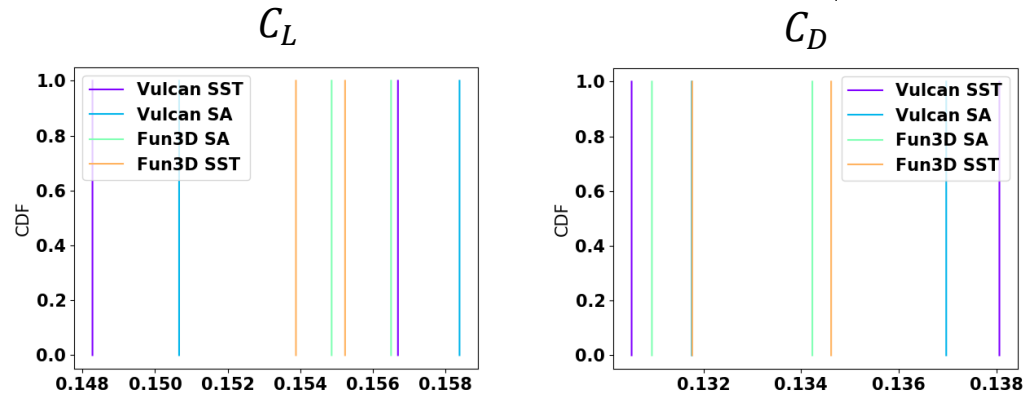


- Simulation were conducted on two turbulence models: SST and SA model for CFD codes FUN3D and VULCAN-CFD
 - Solutions were run until very small changes occurred over 5,000 iterations in L2 norm, mass flow rate, and loads
- The inviscid adjoint CART3D code was also used with a viscous correction term as another comparison point
 - 9 adaption cycles were used and values between the loads were less than 1e-3
- AoA's considered: -4° , 0° , 4° , and 12°

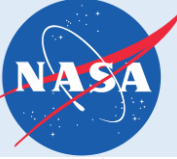
AoA = 4°

Uncertainty Variable	Description	Classification	Lower Bound	Upper Bound
SA Model				
σ	Turbulent Prandtl number	epistemic	0.6	1.0
c_{w2}	Part of g function	epistemic	0.055	0.3525
κ	Von Kármán's constant	epistemic	0.38	0.42
SST Model				
σ_{w1}	coefficient in ω -equation	epistemic	0.3	0.7
σ_{w2}	coefficient in ω -equation	epistemic	0.7	1.0
κ	Von Kármán's constant	epistemic	0.38	0.42

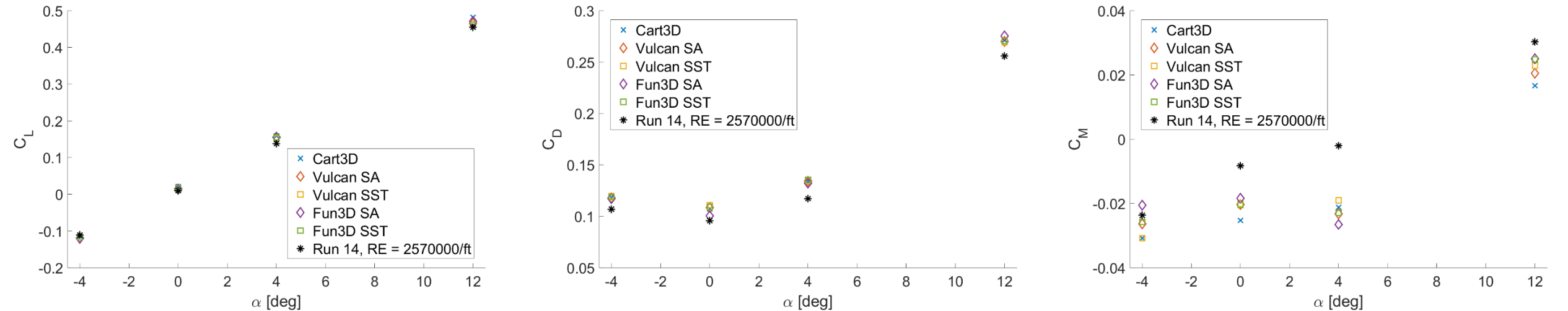
PCE surrogate



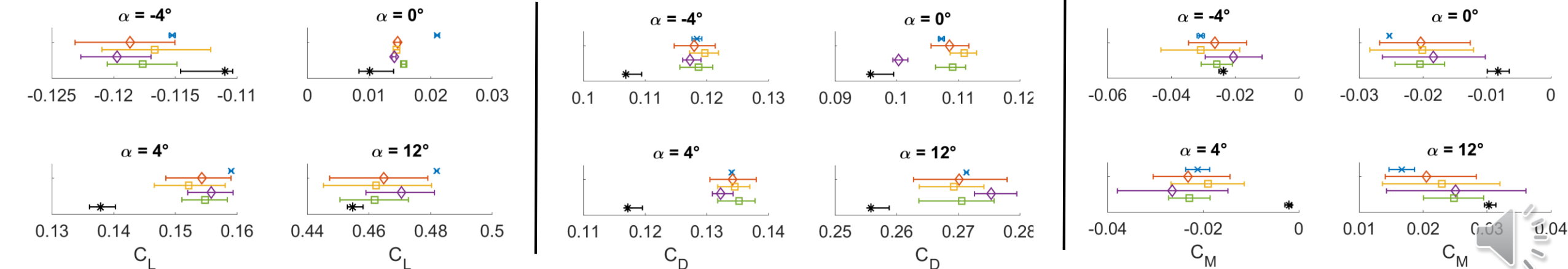
Data Results/Comparison



Comparison of Trends:



Uncertainty Included:



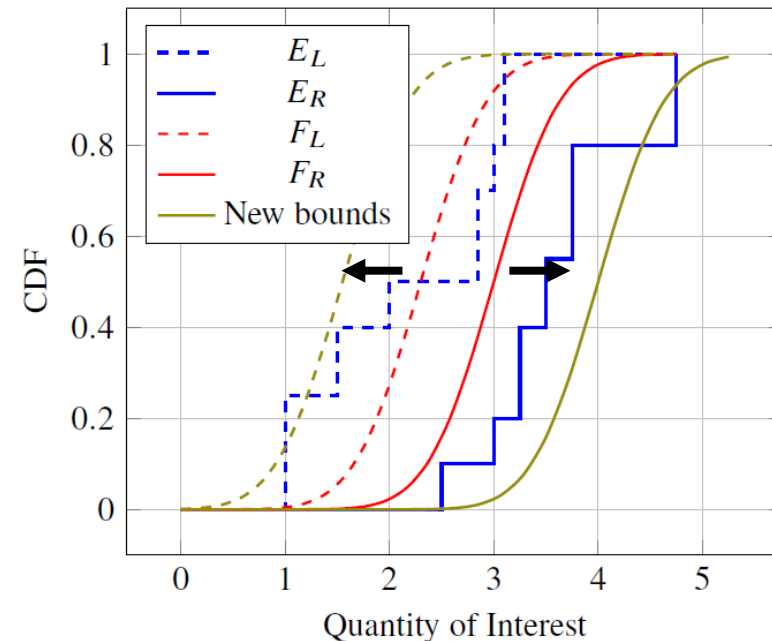
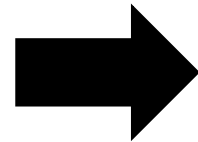
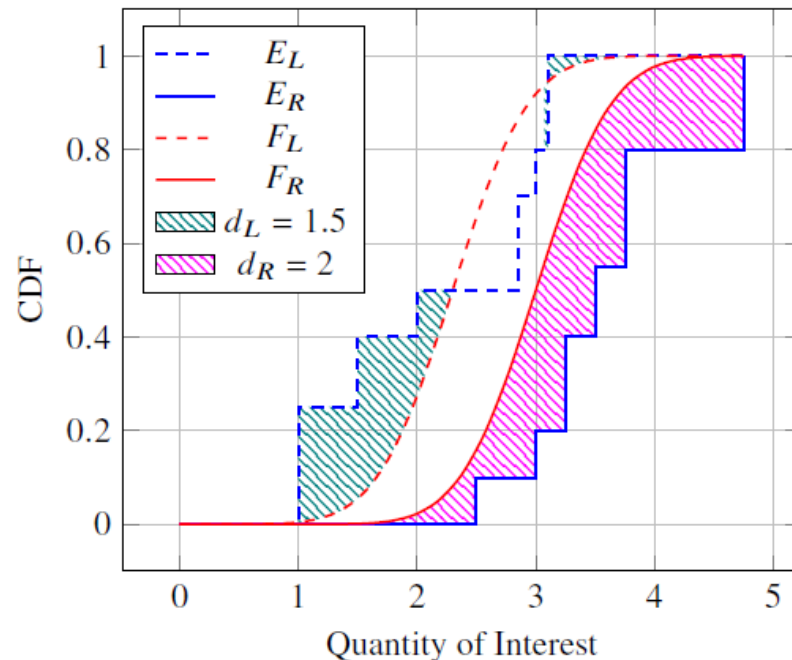
Validation Methodology

- ❖ This work uses a validation metric proposed by Brune et. al in 2019
- ❖ This metric handles disagreement between the left and right bounds of the prediction and experimental distributions separately
 - ❖ This gives a left and right model-form uncertainty which can be added to the uncertainty intervals
- ❖ Take $F(x)$ to represent the CFD's and $E(x)$ to represent the experiment's distributions (CDFs)

$$d_L = \int_{-\infty}^{\infty} g_L(x) dx, \quad d_R = \int_{-\infty}^{\infty} g_R(x) dx$$

$$g_L(x) = \begin{cases} 0 & \text{for } x \text{ s.t. } F_L(x) \geq E_L(x) \\ E_L(x) - F_L(x) & \text{for } x \text{ s.t. } F_L(x) < E_L(x) \end{cases}$$

$$g_R(x) = \begin{cases} 0 & \text{for } x \text{ s.t. } F_R(x) \leq E_R(x) \\ F_R(x) - E_R(x) & \text{for } x \text{ s.t. } F_R(x) > E_R(x) \end{cases}$$

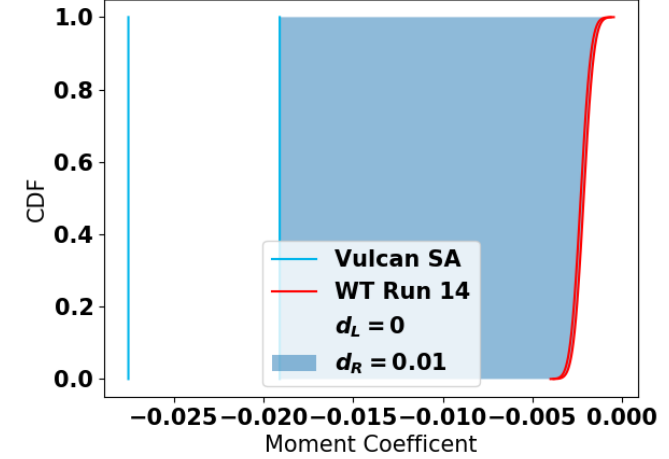
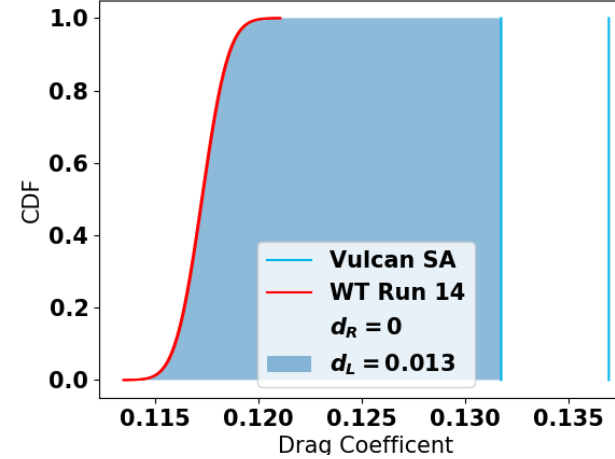
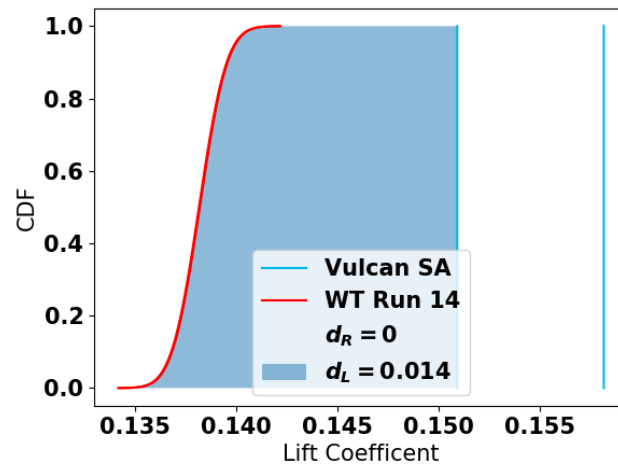


Validation Results

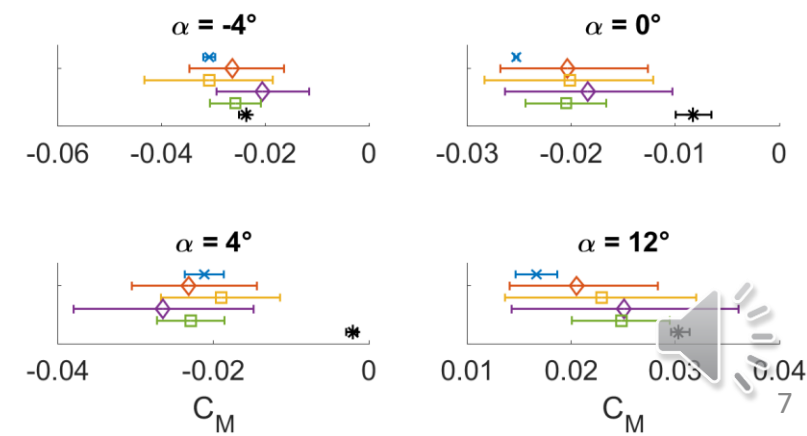
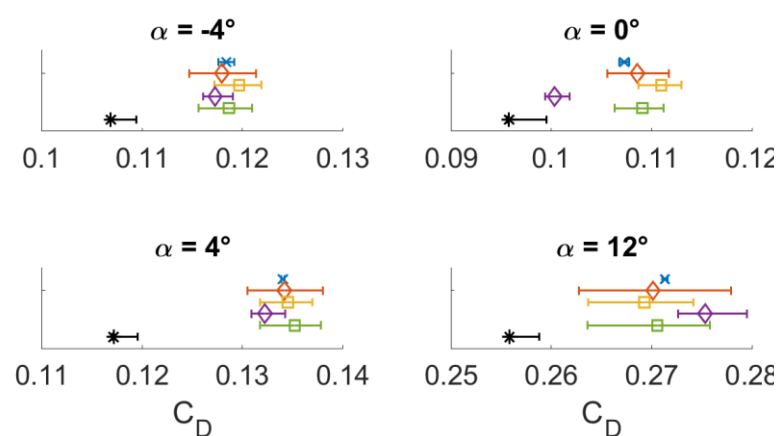
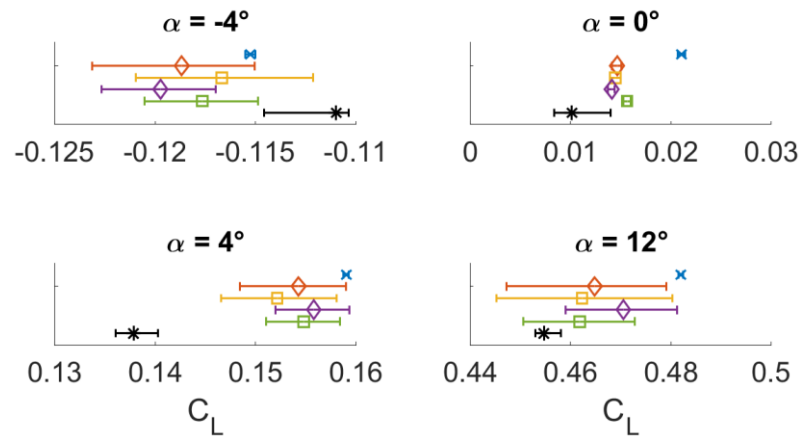
Validation metric between Vulcan SA and Wind Tunnel:

Key findings:

- ❖ The largest model-form uncertainty for the lift accounts for up to a 47% change in the CFD uncertainty interval
- ❖ The largest model-form uncertainty in the drag accounts for 11% change in the CFD uncertainty interval
- ❖ The largest model-form uncertainty for the moment accounts for 86% change in the CFD uncertainty interval



Previous Results:

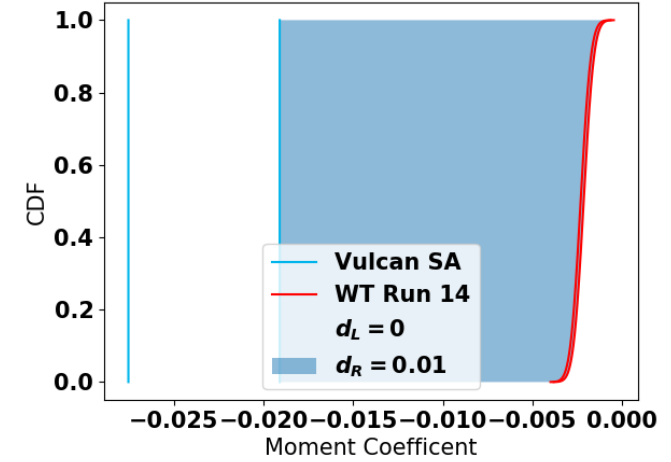
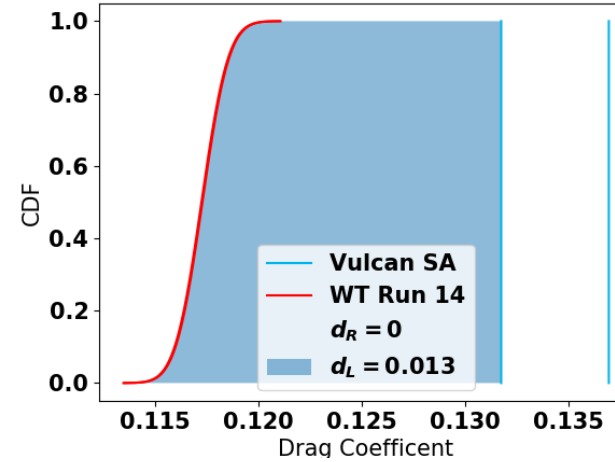
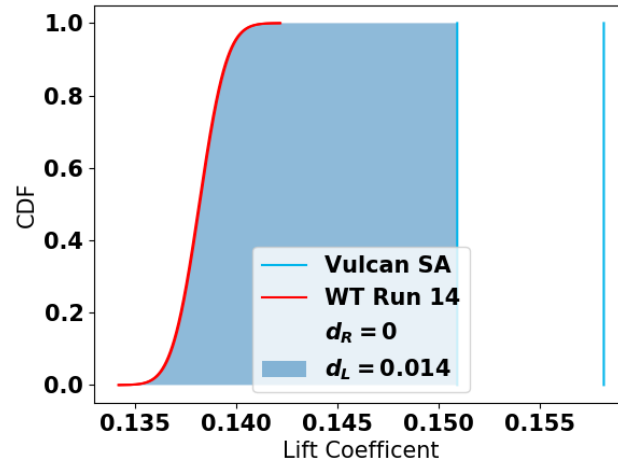


Validation Results

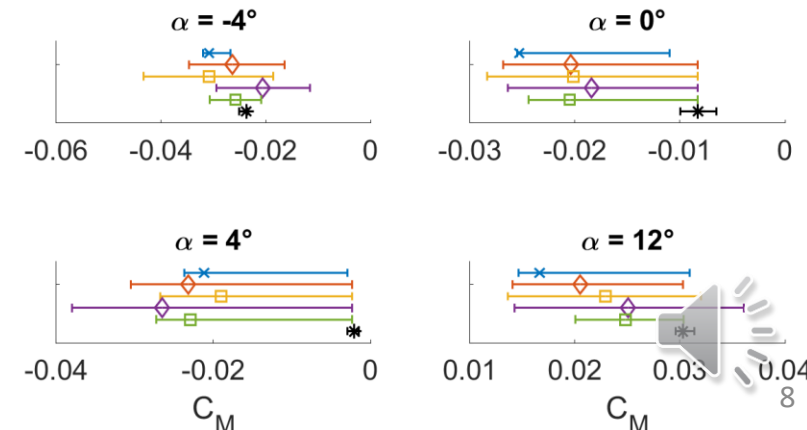
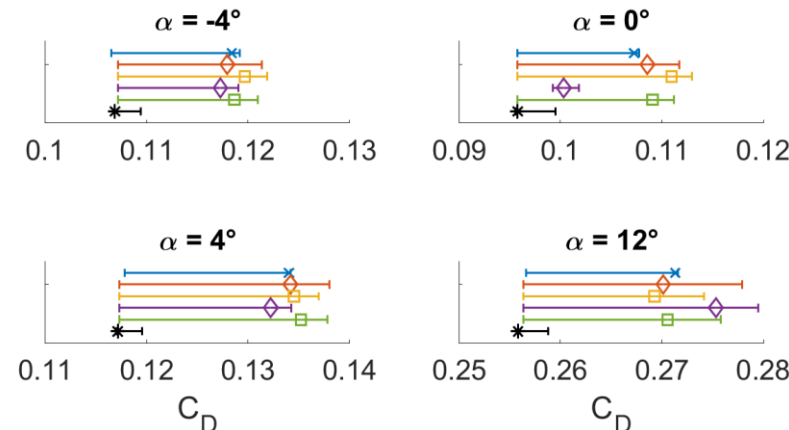
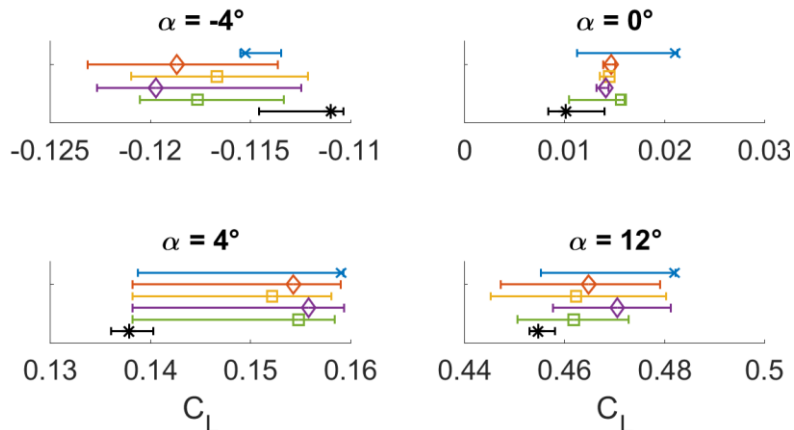
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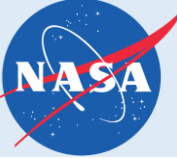
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New results with model-form uncertainty included:

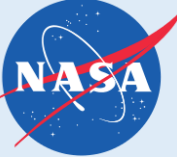


Conclusions



- ❖ The work here shows uncertainty analysis of lift, drag, and moment coefficients for a cone-slice-flap design
- ❖ A validation methodology is implemented to quantify the model-form uncertainty of this type of design
- ❖ Results show that the model-form uncertainty accounts for 47%, 11%, and 86% change in the uncertainty intervals of the CFD models for lift, drag, and moment, respectively
- ❖ Future work includes investigating what is occurring at angle of attack 4° case by performing a higher-fidelity analysis
- ❖ Other future work includes quantifying the uncertainty analysis for the wind-tunnel by using the wind tunnels data reduction codes





Questions?

