



Aerodynamic Fidelity of Ice Accretion Simulation on a Subscale Model

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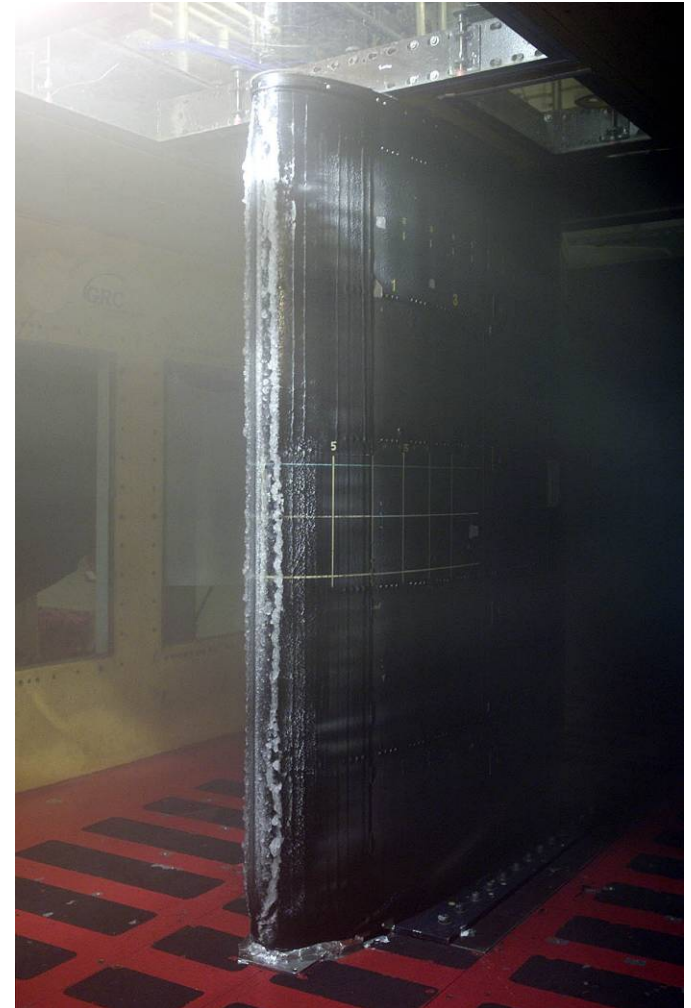
Motivation

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Current Situation

- Simulation at full-scale Re and M with true ice geometry on lifting surfaces is not usually possible.
- Ice accretion codes and scaled ice accretion tests do not produce all ice features accurately.
- Lack of accurate 3-D features affects aerodynamic performance.
- CFD can not yet model full 3-D ice shape aerodynamics accurately.
- Re and M effects not understood on all geometries in scaled tests.





Motivation / Solution

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Problem

- No capability exists to test simulated ice shapes to a known degree of aerodynamic uncertainty
- CFD methods can not model 3-D rough ice shapes accurately
- Need validated aerodynamic simulation methodology

Approach

- Develop simulation methods for subscale aerodynamic testing of Appendix C type ice accretion based on classifications.
- Provide guidance as to the level of fidelity required for accurate ice accretion simulation for accretion codes and CFD analysis.
- Create aerodynamic database for CFD





Research Organization

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- Phase I: Ice Shape Classification
 - Bragg, M.B., Broeren, A.P. and Blumenthal, L.A., “Iced-Airfoil Aerodynamics,” *Progress in Aerospace Sciences*, Vol. 41, No. 5, July 2005, pp. 323-418.
 - Phase II: Subscale Model Ice Accretion Testing
 - Blumenthal, L.A., Master’s Thesis, Univ. of Illinois, 2005.
 - Phase III: Subscale Model Aerodynamic Testing
 - Blumenthal, L.A., Busch, G.T., Broeren, A.P., and Bragg, M.B., “Issues in Ice Accretion Simulation on a Subscale Model,” AIAA Paper 2006-0262.
 - Busch, G.T., Broeren, A.P., and Bragg, M.B., “Aerodynamic Simulation of a Horn-Ice Accretion,” AIAA Paper 2007-0087.
 - Broeren, A.P., Busch, G.T., and Bragg, M.B., SAE Paper 2007-01-3285.
 - Phase IV: Full-scale Model Ice Accretion Testing
 - Phase V: Full-scale Model Aerodynamic Testing
 - Phase VI: Simulation Validation Testing
 - Phase VII: CFD Research
- Overall Program Summary—Bragg, et al., “Airfoil Ice-Accretion Aerodynamic Simulation,” AIAA Paper 2007-0085.



Ice Shape Classification

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Objective: define a small number of fundamental ice shapes based on their unique aerodynamics.

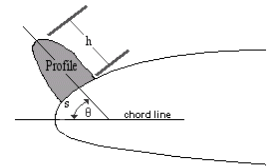
- **Roughness**

- Ice Roughness is larger than the local boundary layer
- Effects determined by height, density, and surface location



- **Horn ice**

- Characterized by large flow separation
- Horn size, location, and angle are key parameters with roughness and the detailed cross-section geometry having little effect



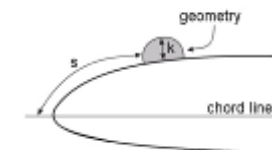
- **Streamwise ice**

- Forms streamlined shape on the leading edge
- Surface roughness can have significant effect on aerodynamics.



- **Spanwise-ridge ice**

- Obstacle in the flow since “airfoil” boundary layer has time to develop
- Location and height are key parameters, but ridge geometry is also important





Objectives and Approach

Objective

- Determine the level of fidelity required to accurately model the aerodynamics of streamwise and spanwise-ridge ice simulations.

Approach

- Conduct aerodynamic testing on a subscale model with simulated ice shapes of varying fidelity.
- Also test high-fidelity, ice-accretion casting simulations to provide the benchmark for comparison.
- Quantify the aerodynamic accuracy of the simulation methods through performance data and flow visualization methods.



Experimental Set-up

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- Aerodynamic testing performed in Univ. of Illinois, 3'x4' low-speed wind-tunnel.
- Model was an 18-inch chord NACA 23012 airfoil and had a removable leading edge to facilitate various ice shape simulations.
- Lift and pitching moment were determined from a floor force balance and integrated surface static pressures.
- Drag was measured with a wake-survey rake.
- All testing was conducted at $Re = 1.8 \times 10^6$ and $M = 0.18$.
- Surface-oil flow visualization was also performed to document major flowfield features.



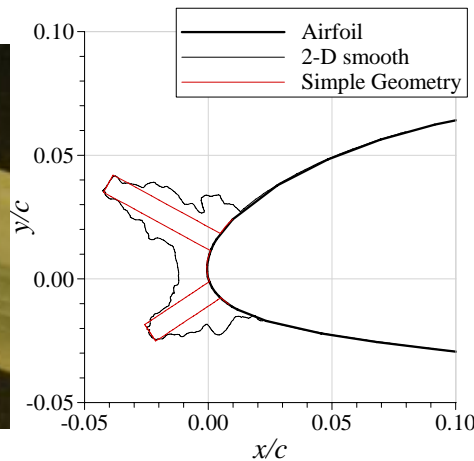
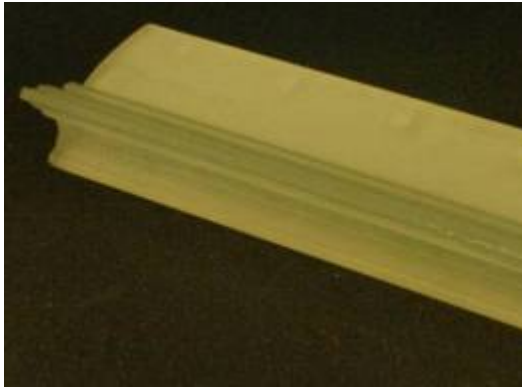
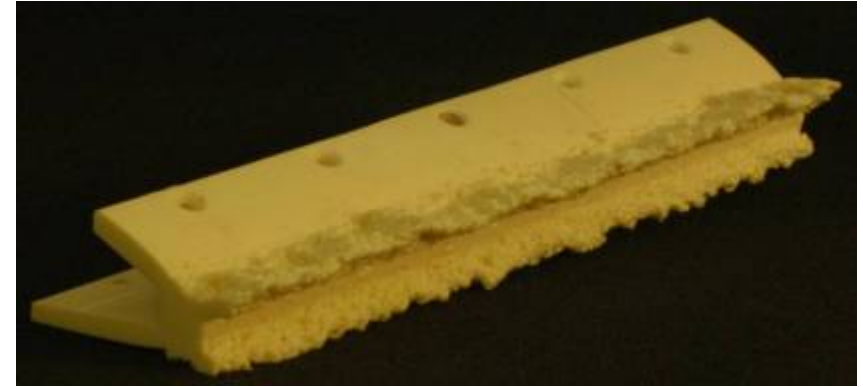


Ice Shape Simulation Methods

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- **3-D casting**
 - From mold of ice accretion
 - Captures most of the geometric detail



2-D smooth based on smoothed coordinates from ice tracing
2-D simple geometry uses basic geometric shape(s)

- **3-D simulation**
 - Grit roughness added to the 2-D simulations





Results—Streamwise Ice Shape

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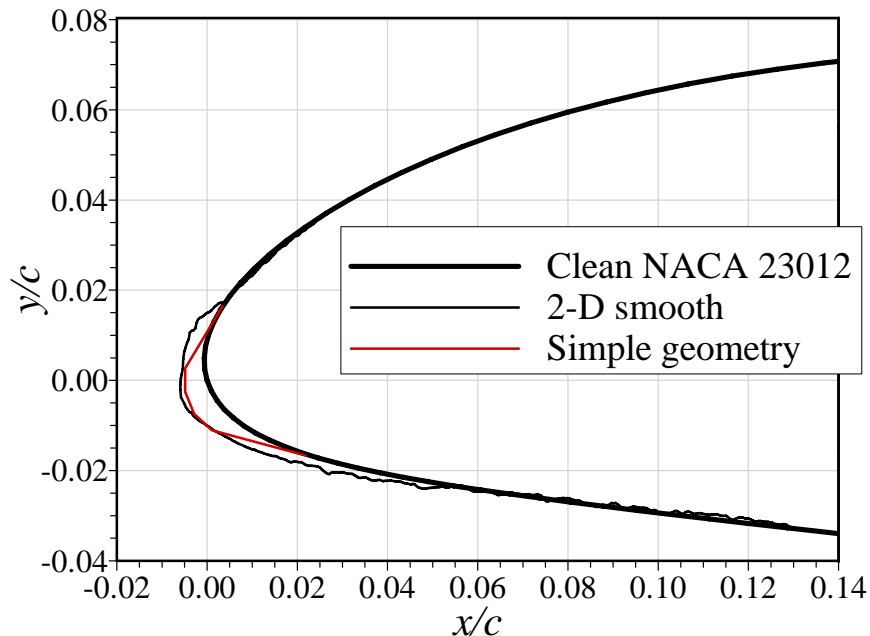
Streamwise ice shape simulation



Ice accretion



Ice casting segment



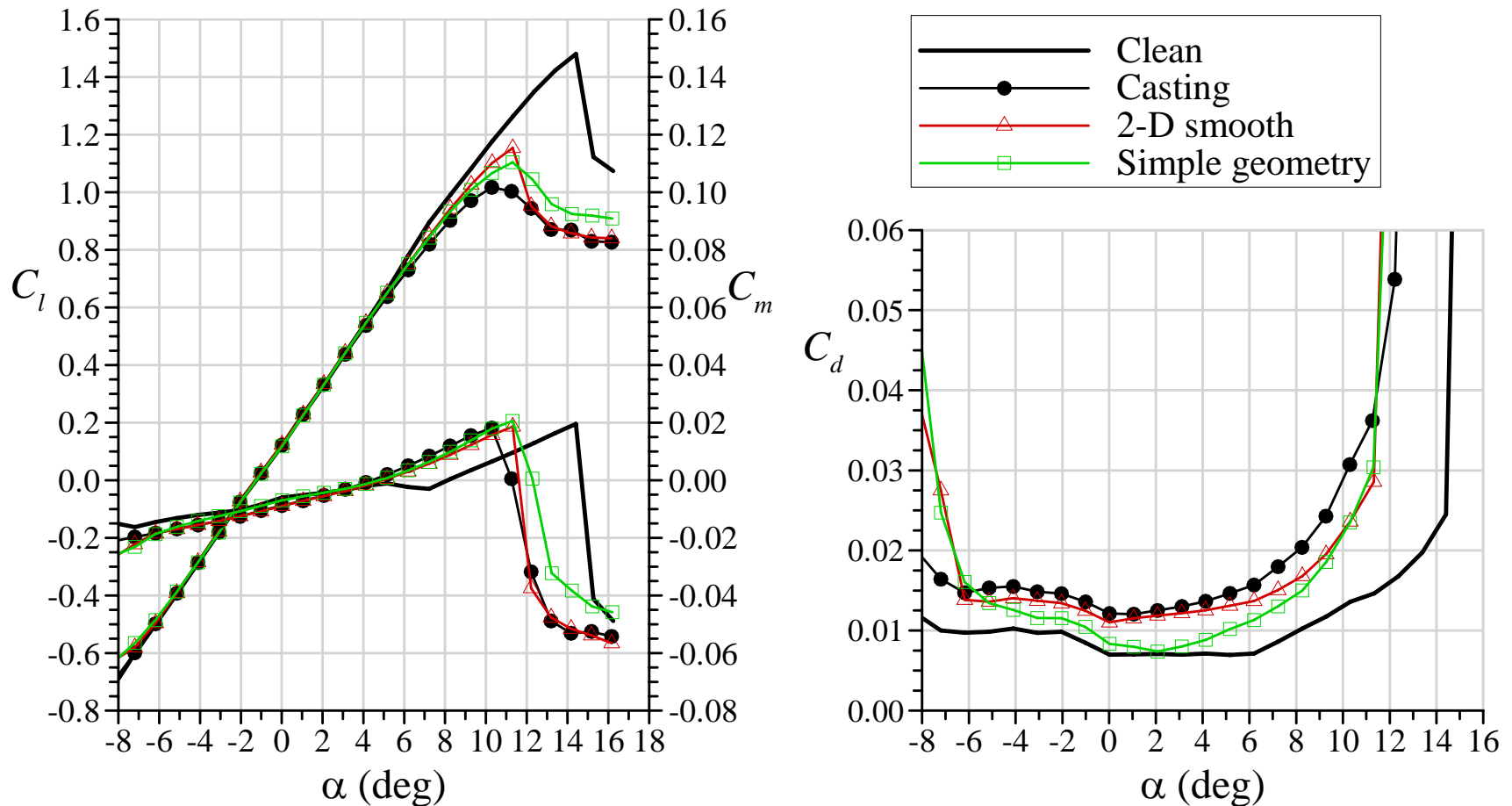
2-D Simulations

- 2-D smooth, manufactured using stereolithography
- Simple geometry, manufactured with simple materials applied to leading edge of clean model.
- Distributed roughness was added to the 2-D simulations.



Results—Streamwise Ice Shape

Comparison of baseline simulation methods.



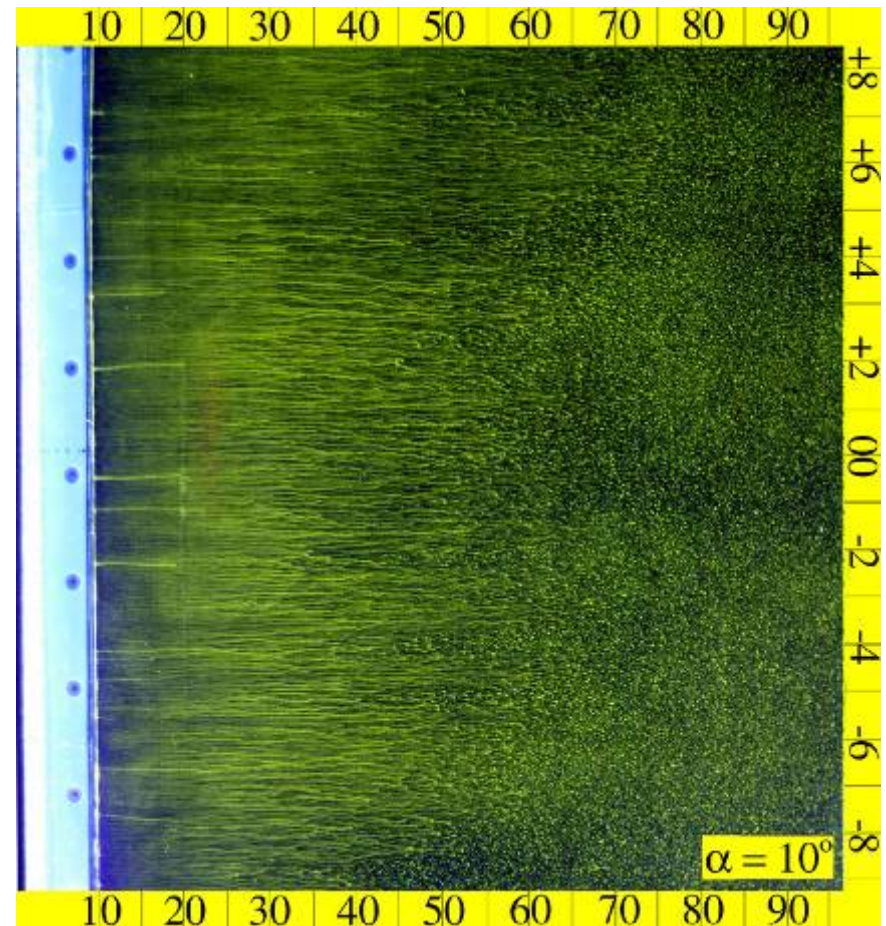
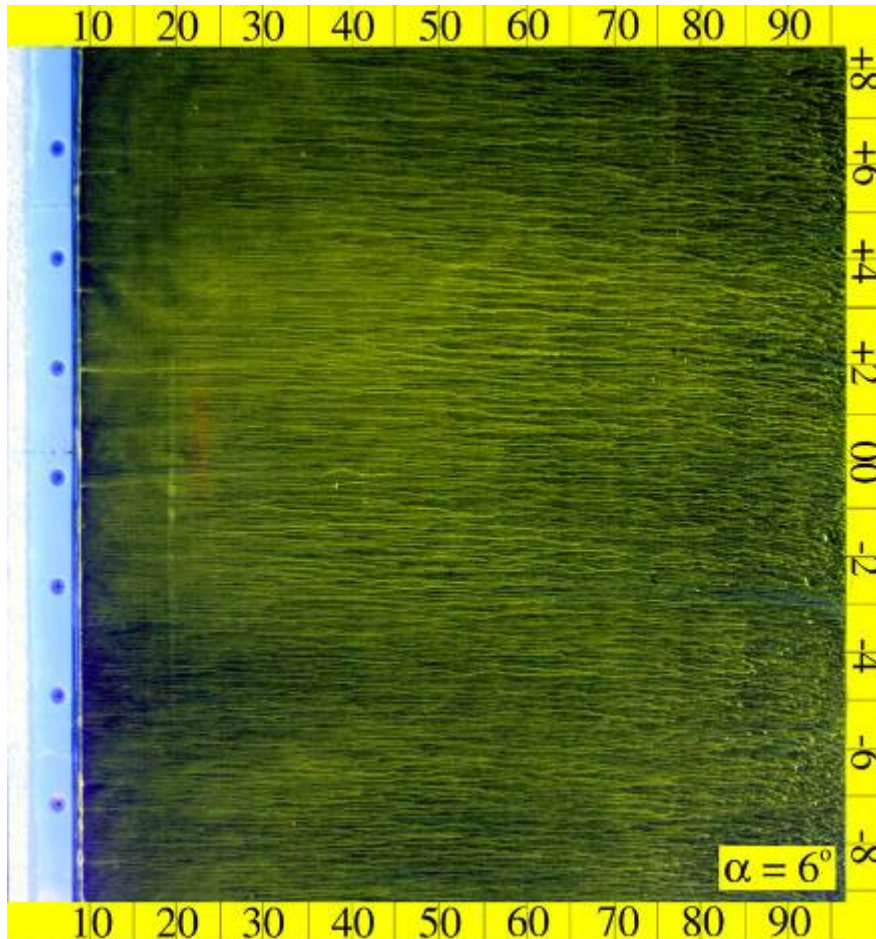


Results—Streamwise Ice Shape

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Flow visualization images for casting simulation.



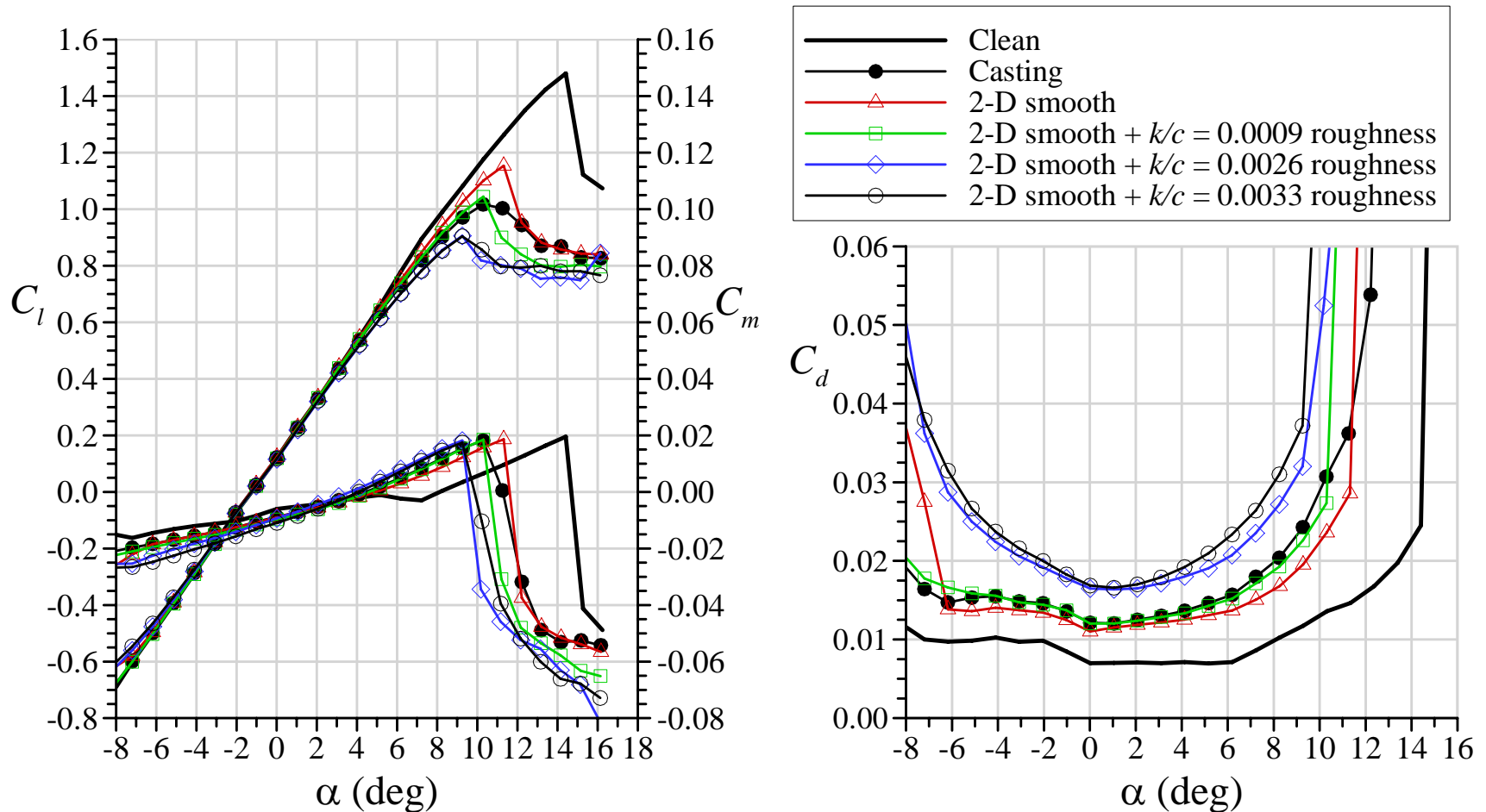


Results—Streamwise Ice Shape

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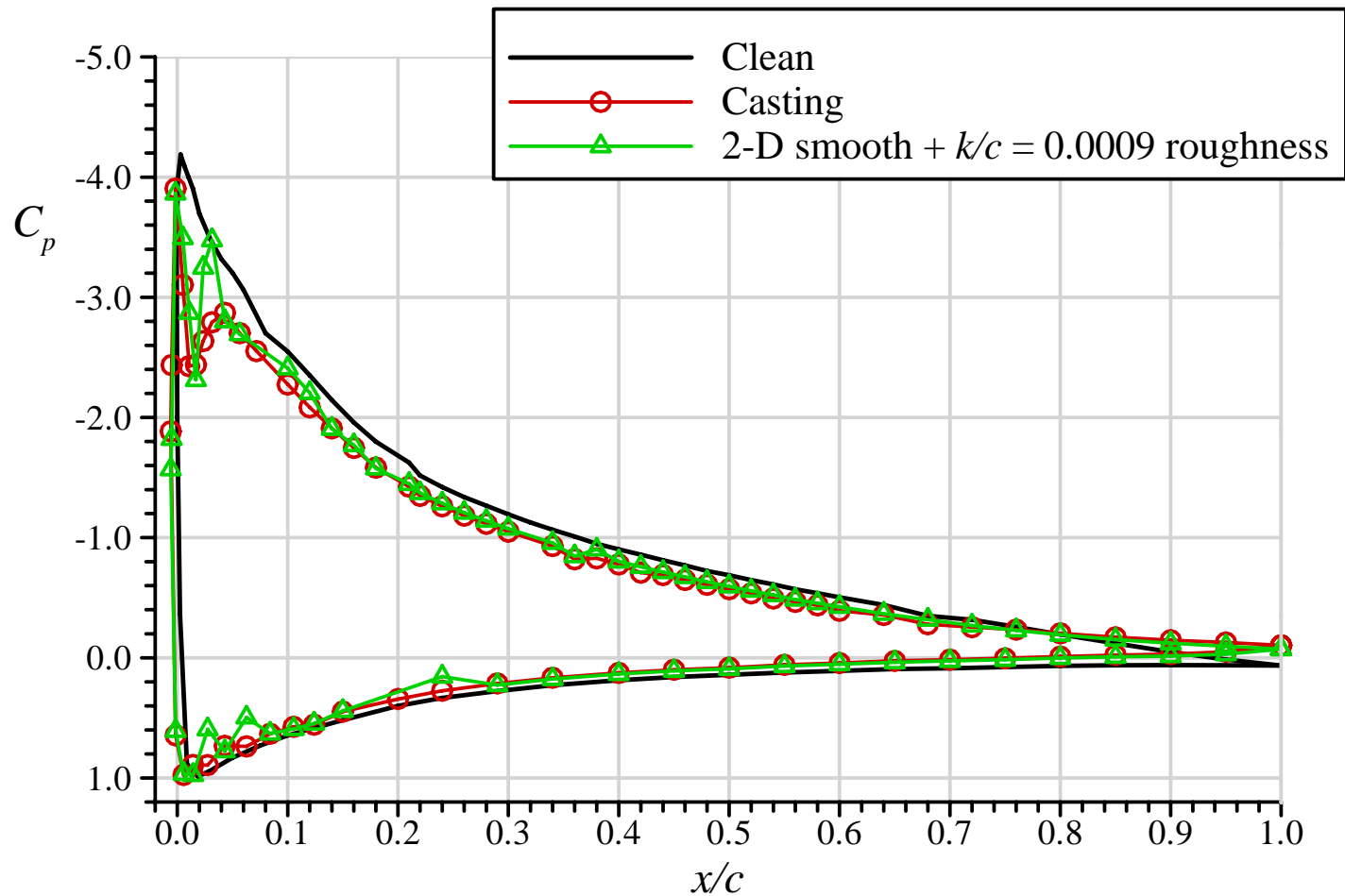
Effect of roughness applied to 2-D smooth simulation.





Results—Streamwise Ice Shape

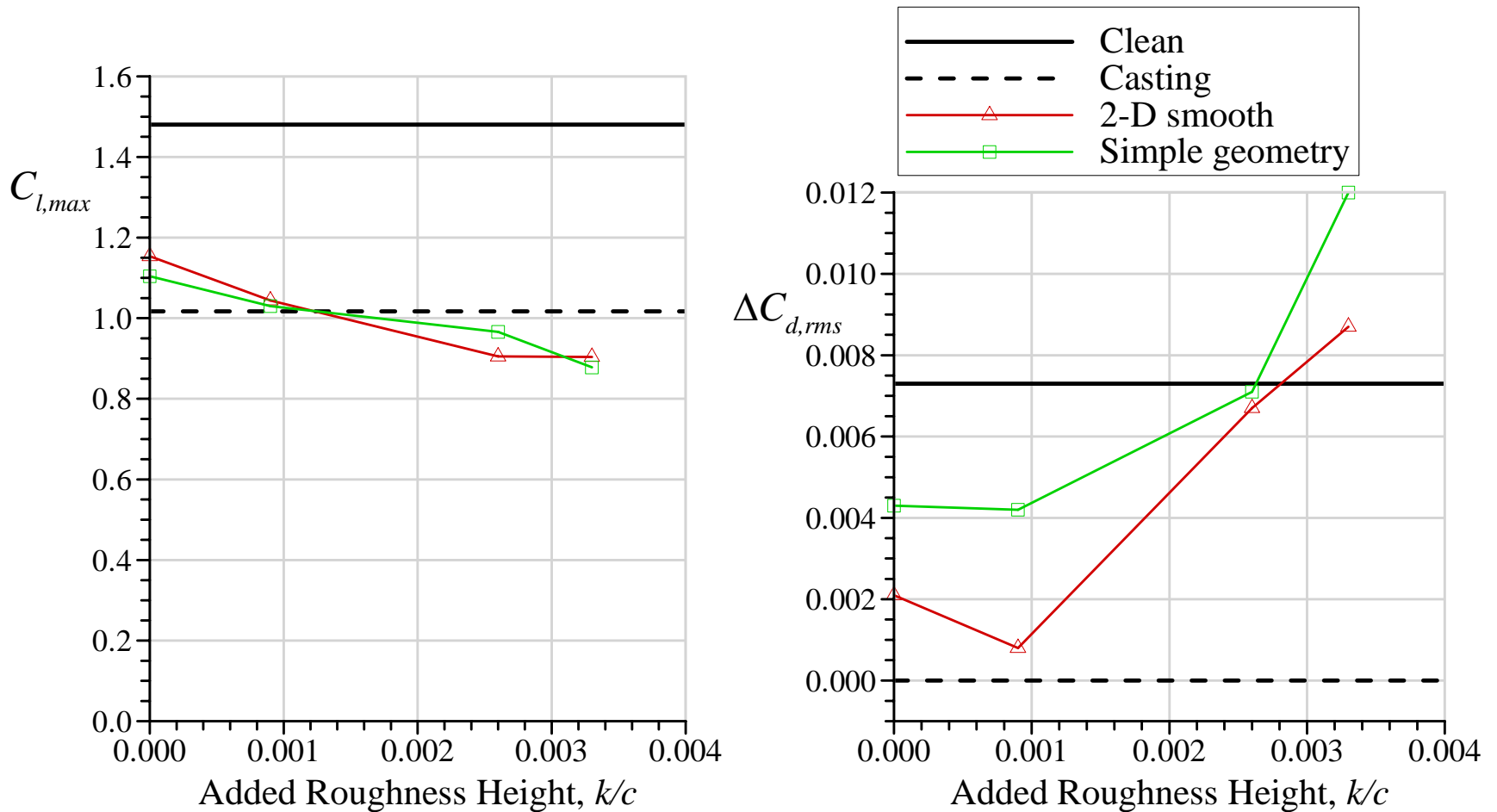
Surface pressure distribution comparison at AoA = 10.3 deg.





Results—Streamwise Ice Shape

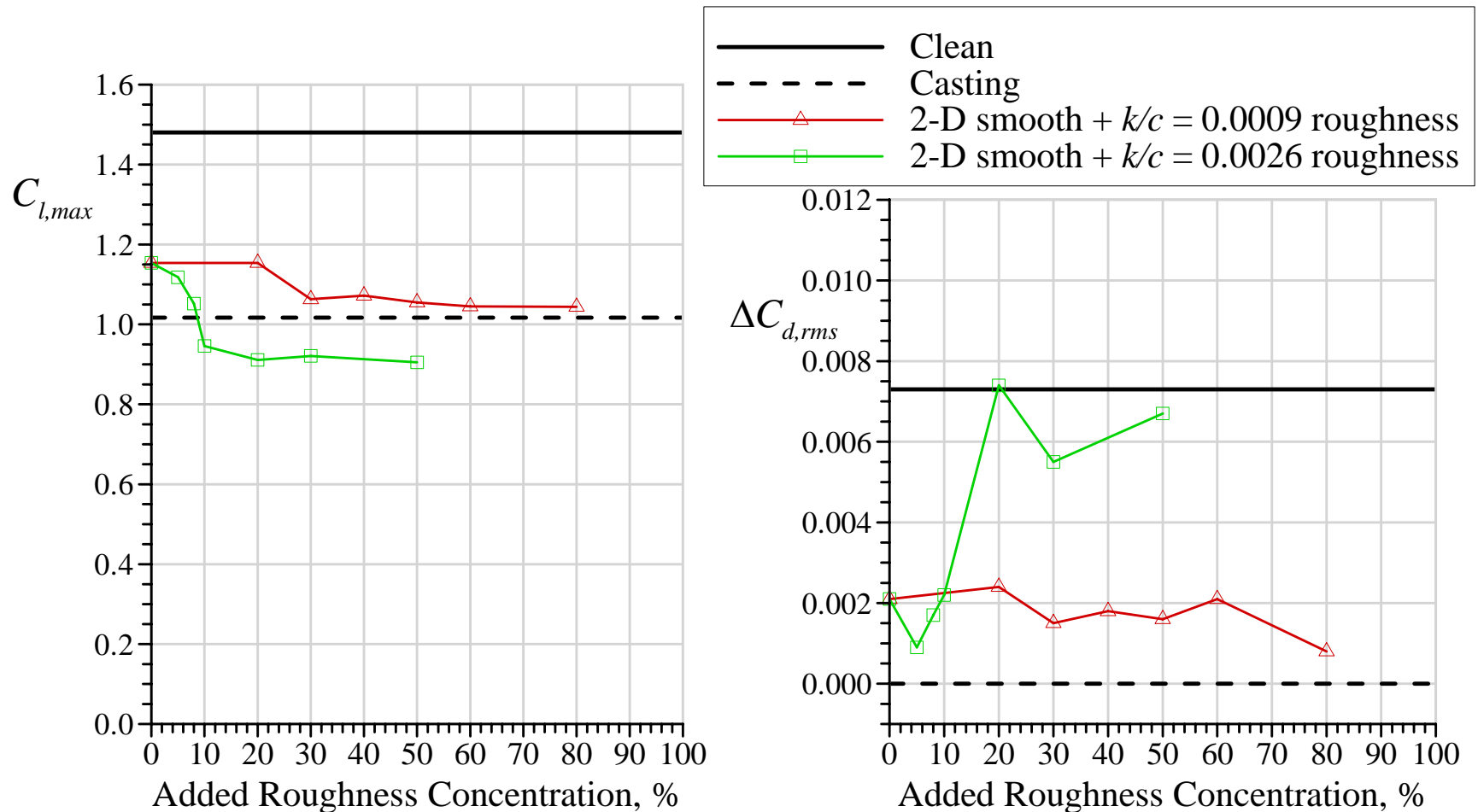
Effect of added roughness size on lift and drag.





Results—Streamwise Ice Shape

Effect of added roughness concentration on lift and drag.





Summary—Streamwise Ice Shape

- The lower fidelity, 2-D simulations of streamwise ice resulted in lower drag and lift penalty than for the high-fidelity 3-D casting simulation.
- The ice surface roughness on the 3-D casting caused trailing-edge separation to develop on the model at lower angles of attack than for the 2-D simulations.
- Distributed grit roughness was added to the 2-D simulations to improve the aerodynamic accuracy.
- A roughness size of $k/c = 0.0009$ with an 80% concentration applied to the 2-D smooth simulation provided the best aerodynamic matching.
 - However, estimates of the actual roughness size from the casting, were larger and lower in concentration.
 - The use of larger grit sizes at lower concentrations on the 2-D simulations resulted in less effective aerodynamic matching to the 3-D casting.

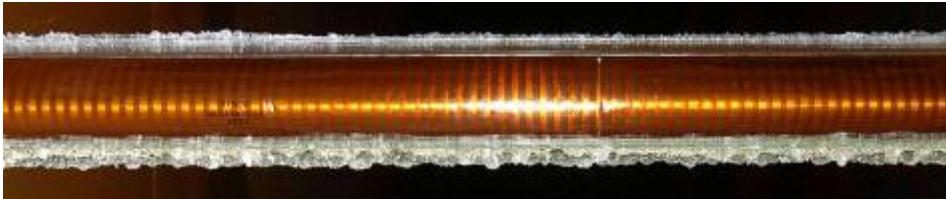


Results—Spanwise-Ridge Ice Shape

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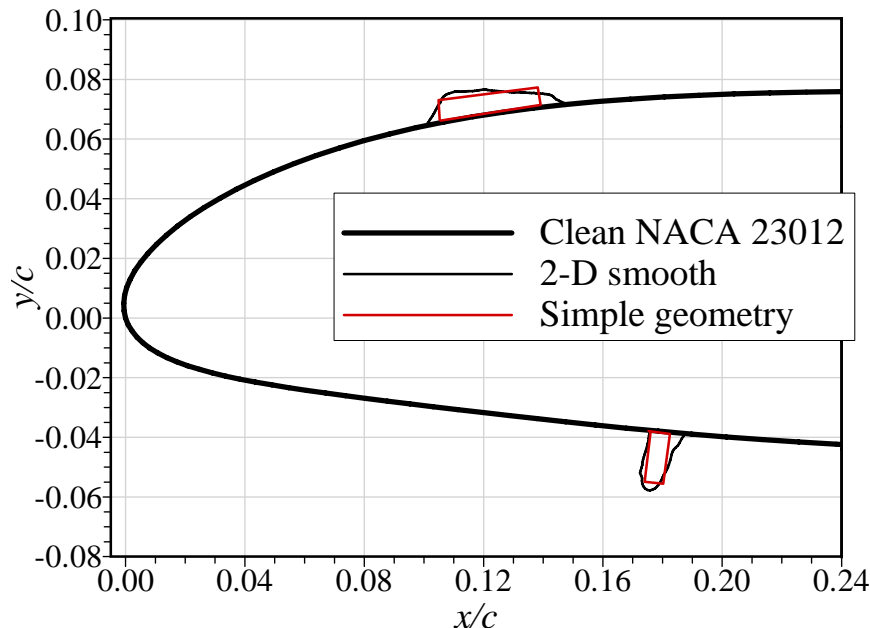
Spanwise-ridge ice shape simulation



Ice accretion



Ice casting segment



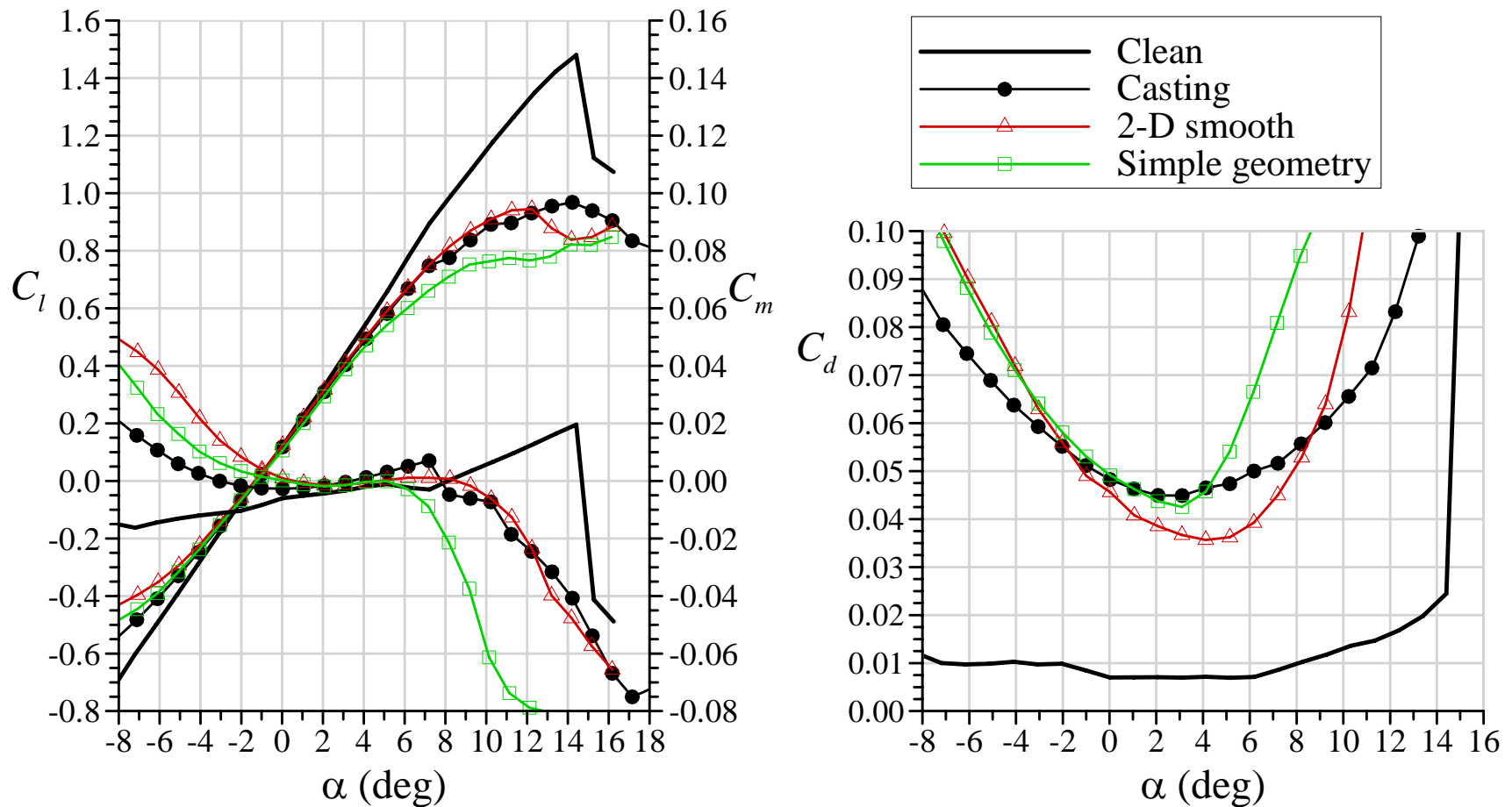
2-D Simulations

- 2-D smooth, manufactured using stereolithography
- Simple geometry, manufactured with simple materials applied to leading edge of clean model.
- Distributed roughness was added to the 2-D simulations.



Results—Spanwise-Ridge Ice Shape

Comparison of baseline simulations methods.



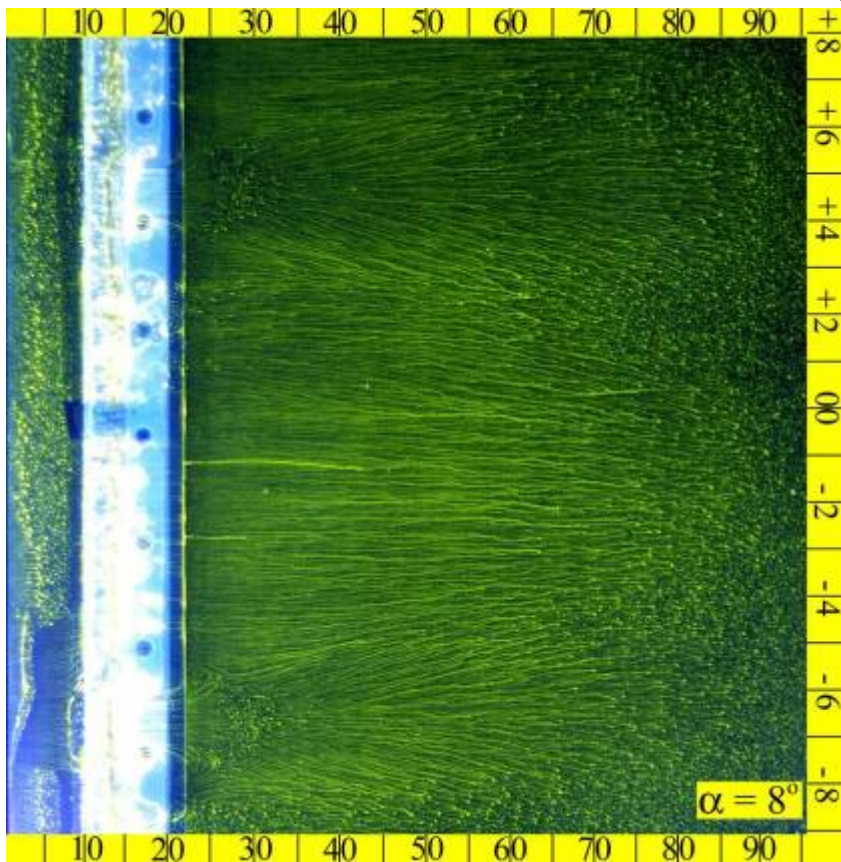


Results—Spanwise-Ridge Ice Shape

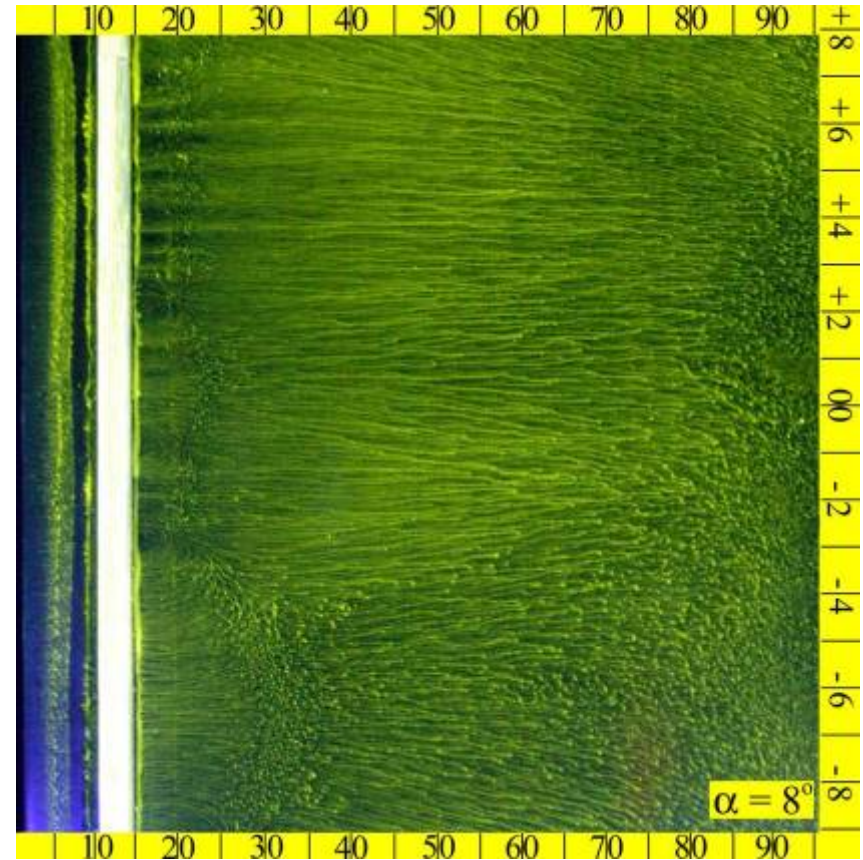
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Flow visualization images for casting and simple geometry simulations at $\text{AoA} = 8^\circ$.



Casting

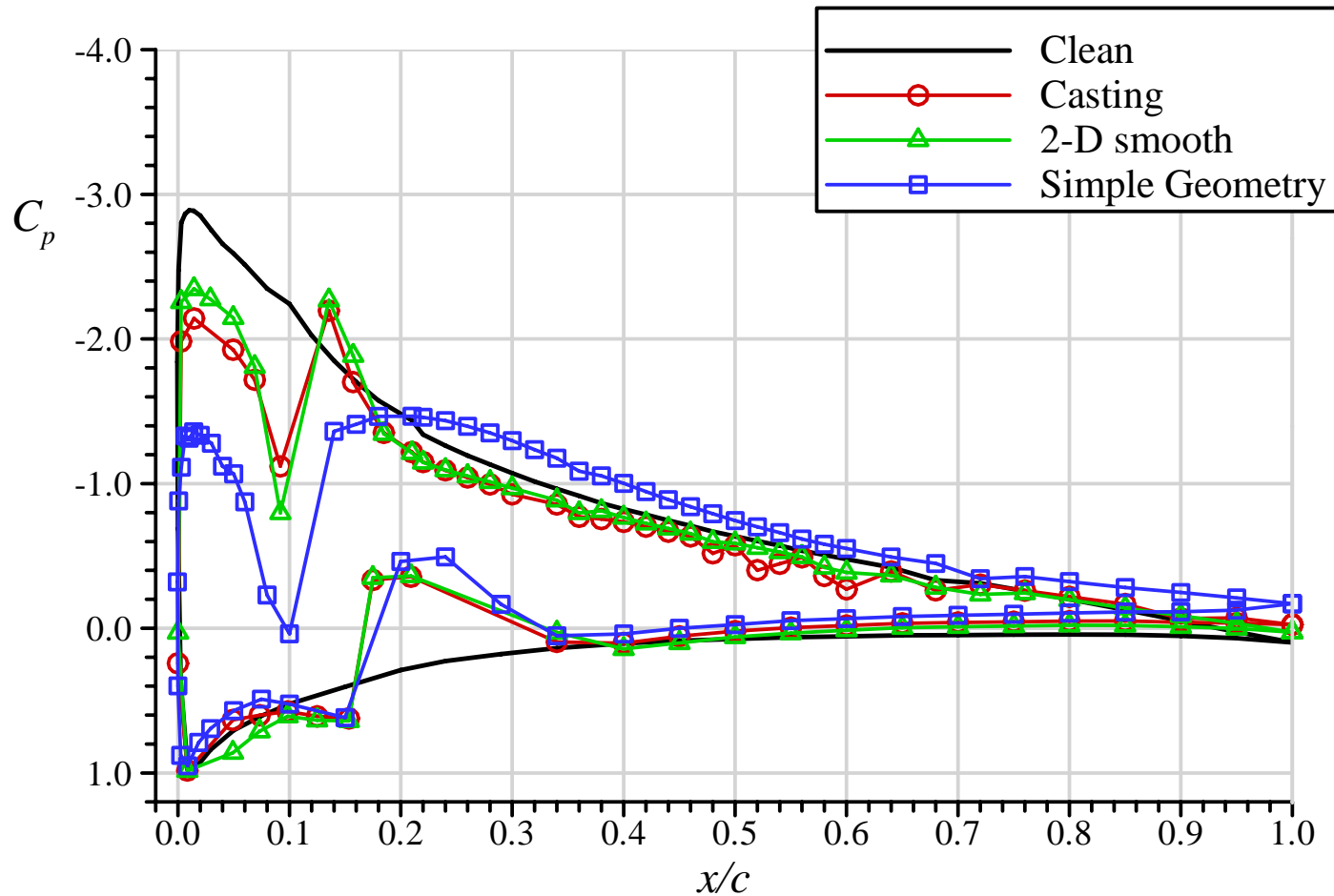


Simple Geometry



Results—Spanwise-Ridge Ice Shape

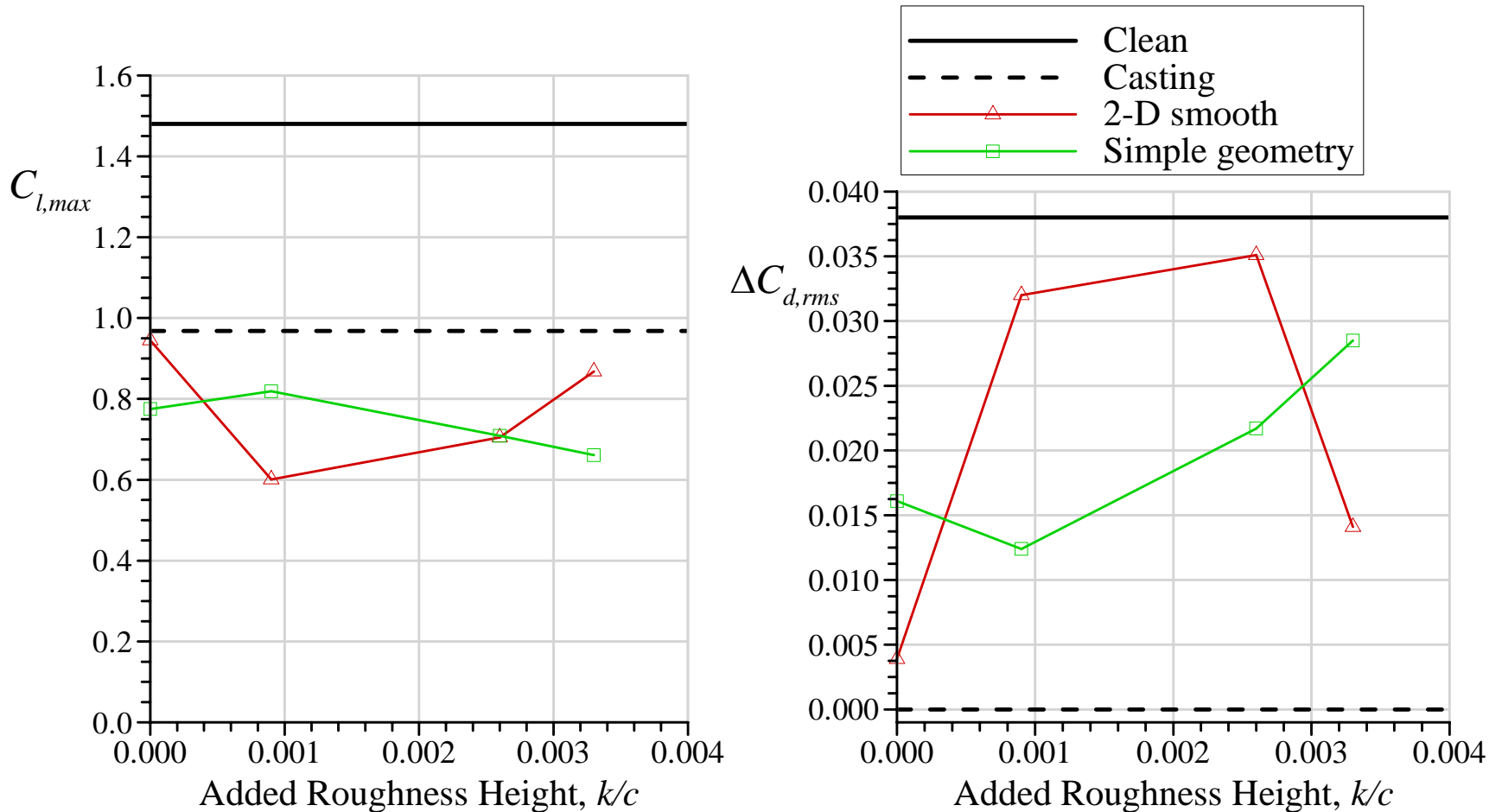
Surface pressure distribution comparison at AoA = 8.2 deg.





Results—Spanwise-Ridge Ice Shape

Effect of added roughness size on lift and drag.





Summary—Spanwise-Ridge Ice Shape

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- The spanwise-ridge casting simulation resulted in a highly 3-D separation bubble aft of the upper surface ridge and 3-D trailing-edge separation for angles of attack near stall.
 - This was likely due to the 3-D geometric features of the upper surface ridge and its relatively small height ($k/c = 0.007$).
- This complex flowfield was difficult to reproduce with the lower-fidelity simulations.
- The 2-D smooth simulation was provided the best matching in aerodynamic performance.
- The addition of roughness did not improve the simulation.
- A better understanding of the complex flowfield is required to develop better simulations.



Simulation Effectiveness

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Simulation	Simulation $C_{l,max}$ - Casting $C_{l,max}$	Simulation α_{stall} - Casting α_{stall} (deg)	Δ RMS C_d between Simulation and Casting
Horn Ice			
2-D smooth	0.001	0.0	0.0054
Simple geometry	-0.013	0.0	0.0062
2-D smooth + 80% $k/c = 0.0009$	-0.017	0.0	0.0079
SG + 80% $k/c = 0.0009$	-0.020	0.0	0.0052
Streamwise Ice			
2-D smooth	0.137	1.0	0.0021
Simple geometry	0.087	1.0	0.0043
2-D smooth + 80% $k/c = 0.0009$	0.027	0.0	0.0008
SG + 80% $k/c = 0.0009$	0.013	0.0	0.0042
Spanwise-Ridge Ice			
2-D smooth	-0.023	-2.0	0.0039
Simple geometry	-0.193	-3.1	0.0161
2-D smooth + 50% $k/c = 0.0033$	-0.100	-2.0	0.0141
SG + 80% $k/c = 0.0009$	-0.149	-4.1	0.0124



Conclusions

- The results of the subscale simulation research suggests that different simulation methods should be used for different types of ice shapes.
- For horn ice the dominance of the separation bubble in the flowfield made the 2-D smooth and simple geometry simulations nearly equal in effectiveness. The addition of roughness generally decreased the simulation aerodynamic accuracy.
- For streamwise ice simulations, the trailing-edge stall characteristics led to the addition of roughness to the 2-D smooth simulation for accurate aerodynamics. The size and concentration of roughness should also be taken into account.
- For the spanwise-ridge ice shape considered in this study, the iced-airfoil flowfield near stall was highly three-dimensional. This led to difficulty in determining the best aerodynamic simulation method. More research is needed to understand the aerodynamics of similar “small” spanwise-ridge ice shapes.



Future Work

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- The **Phase V: Full-scale Aerodynamic Testing** was conducted in April-May of 2007.
- High-fidelity ice casting simulations were tested on a 72-inch chord NACA 23012 model at flight Reynolds number at the ONERA F1 facility.
- These results will be presented at the AIAA meeting in Reno.
- The **Phase VI: Simulation Validation Testing** is currently being conducted at the Univ. of Illinois.
- The full-scale ice shapes will be simulated for testing on the 1/4-scale model at lower Reynolds number.
- These resulted will be presented at a future meeting.

