Machine learning based Airfoil Performance Model for rough and eroded conditions

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and Protection of Wind Turbine Blades
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What is the APM?

The Airfoil Performance Model estimates the aerodynamic performance of an airfoil taking into account its **surface status** by means of **machine learning** algorithms

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What is the APM?

The Airfoil Performance Model estimates the aerodynamic performance of an airfoil taking into account its **surface status** by means of **machine learning** algorithms

Applicability to wind turbine Blades, covering airfoils at the 25% outermost part of the blade

General use, extrapolation to airfoils not considered within the dataset

High fidelity results with smaller simulation time than CFD

Accurate prediction of the aerodynamic performance of an airfoil considered in the training dataset

Capability to determine the influence of the surface status on the aerodynamic performance

AEP Losses stimations

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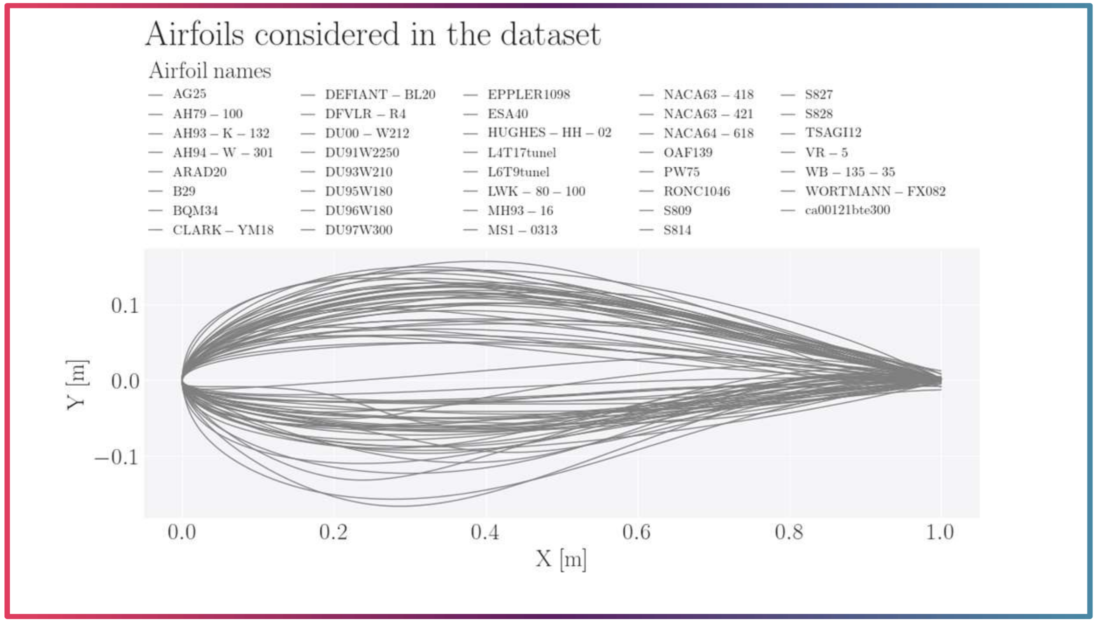
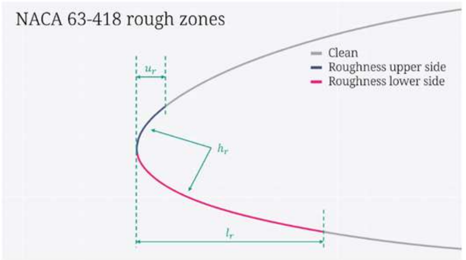
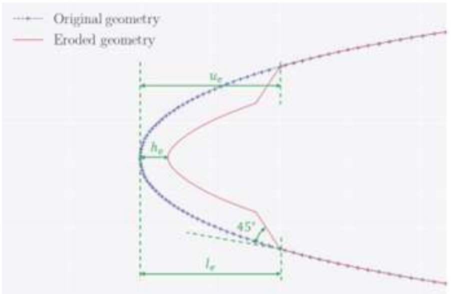
Training Dataset

- 39 airfoils
- Simulated using CFD for clean, rough and erosion conditions (3465 simulations per airfoil)
- Thickness limited to 7,5% - 30%
- Reynolds from 6 to 12 million





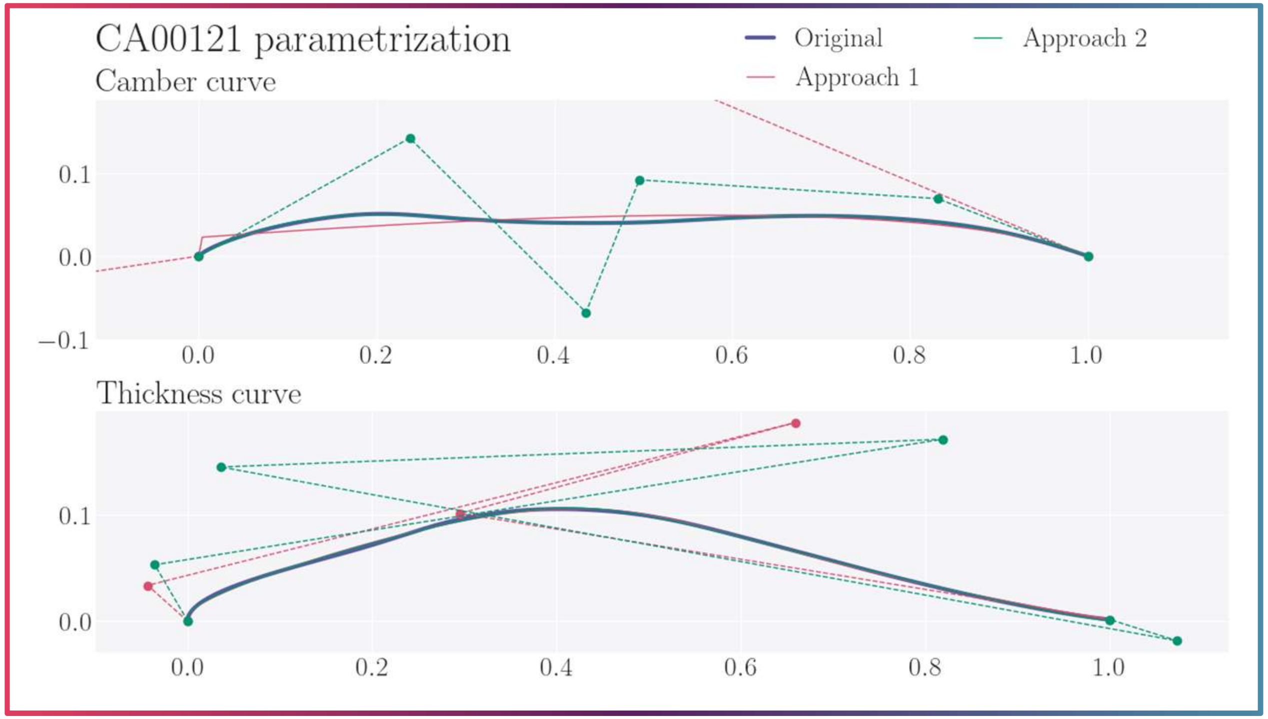


Training Dataset

Bezier parametrization

- Based on XFoil coordinate file with 345 points
- Camber and thickness curves obtained following the British convention
- Camber and thickness curves fitted to n-th degree Bezier curve represented by n+1 control points
- Restrictions:

First and last points coincident with the curve
Second point of the thickness curve forced to be on the vertical direction of the first point



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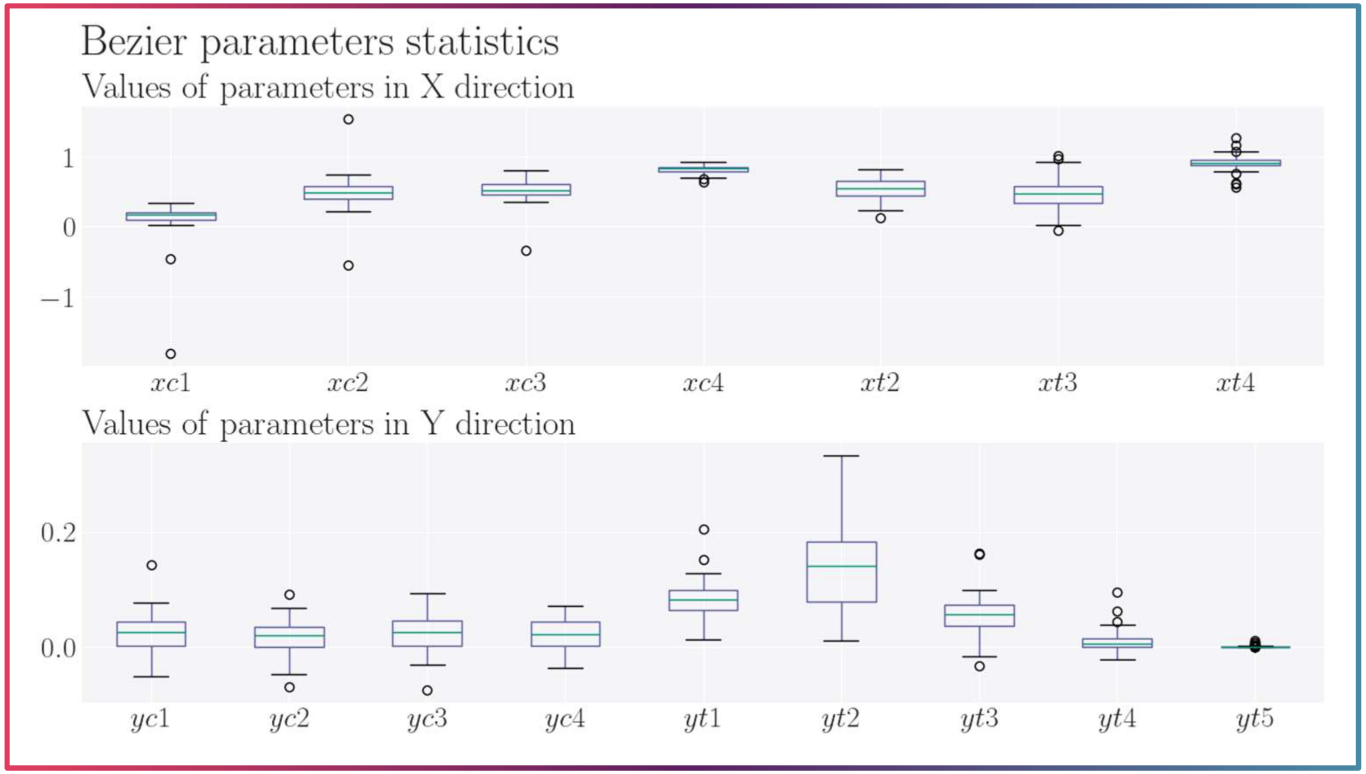
Training Dataset

Geometrical Parameters distribution

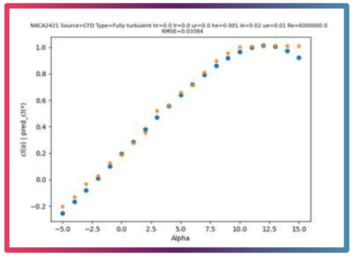


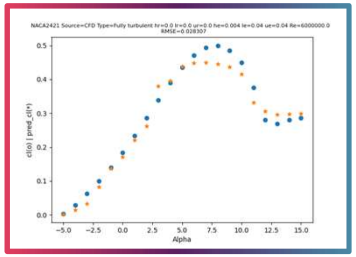
ML algorithm selection

Algorithm	Advantages	Disadvantages
Random Forests, RF	Robustness to overfitting due to ensemble averaging	Can be computationally intensive for very large datasets
	Capability to handle large datasets with different types of variables (categorical, numerical …)	May require significant memory for storing multiple trees
	Less need for extensive feature engineering	Less effective for extrapolating beyond the range of training data
	Good performance with minimal tuning	Predictions can be less smooth compared to continuous models
	Provides feature importance, aiding in model interpretability	
Neural Networks, NN	High flexibility in modelling complex and non-linear relationships	Requires large amounts of data for effective training
	Can handle very large and high-dimensional datasets effectively	May require specialized hardware and can be computationally intensive
	Suitable for capturing interactions between variables	Prone to overfitting without proper regularization
	Potential to achieve high accuracy with proper tuning and sufficient data	Require extensive hyperparameter tuning and are challenging to interpret

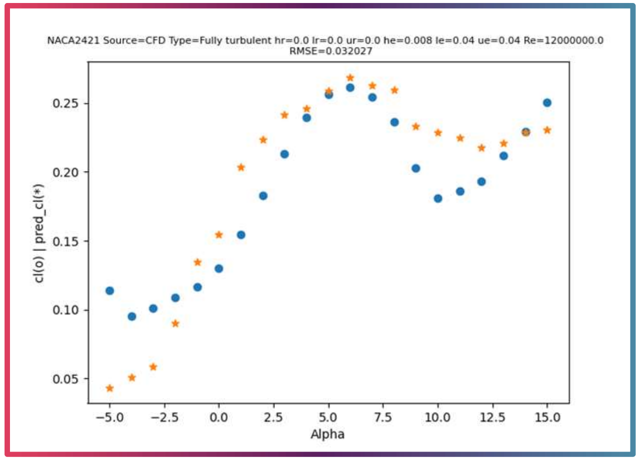
ML algorithm selection

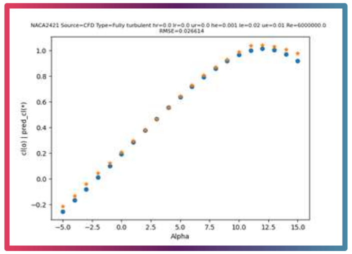
(NACA 2421 not included in the training dataset)

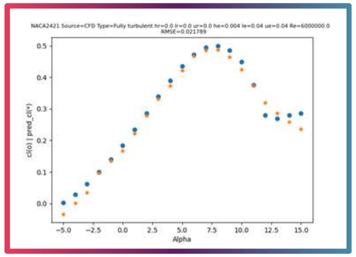




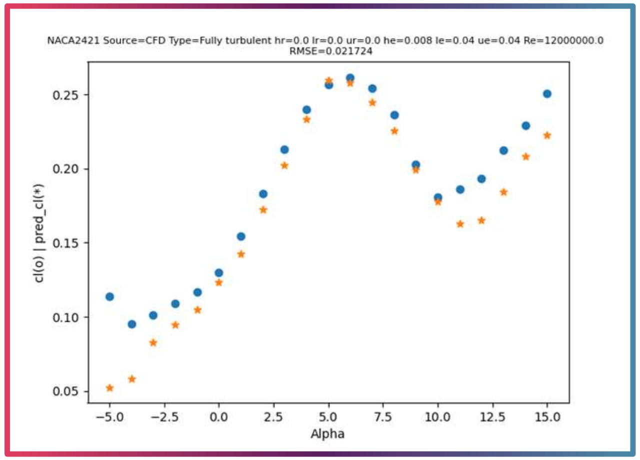
RMSE 0,032







RMSE 0,022



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Final models

- Neural networks are employed
- One model trained for each coefficient and condition resulting in 6 models
- 3465 simulations per airfoil
- Include clean, rough and eroded conditions

Model		Layers	Nodes per layer
Roughness	Lift	4	512
	Drag	4	512
	Efficiency	2	200 and 100
Erosion	Lift	2	500 and 250
	Drag	2	500 and 250
	Efficiency	2	500 and 250

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Three tests selected

Test 1: three airfoils used for the training are tested at different rough conditions and Reynolds numbers from the ones used to create the dataset

Test 2: six new airfoils stimated with the rough model (3 of them are high thickness and complex thickness and camber curves)

Test 3: 26 airfoil tested with the erosion model for conditions excluded from training and validation phases

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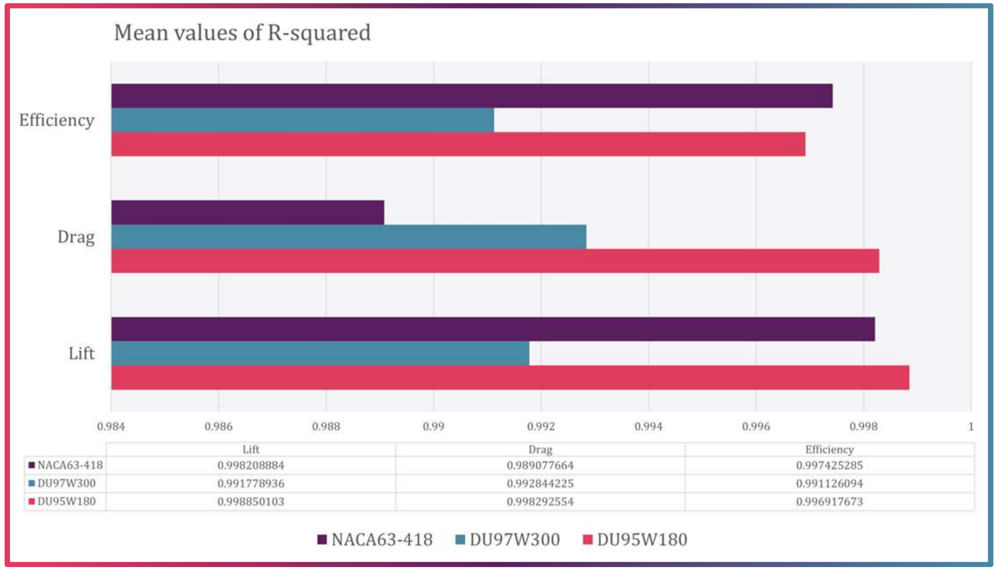
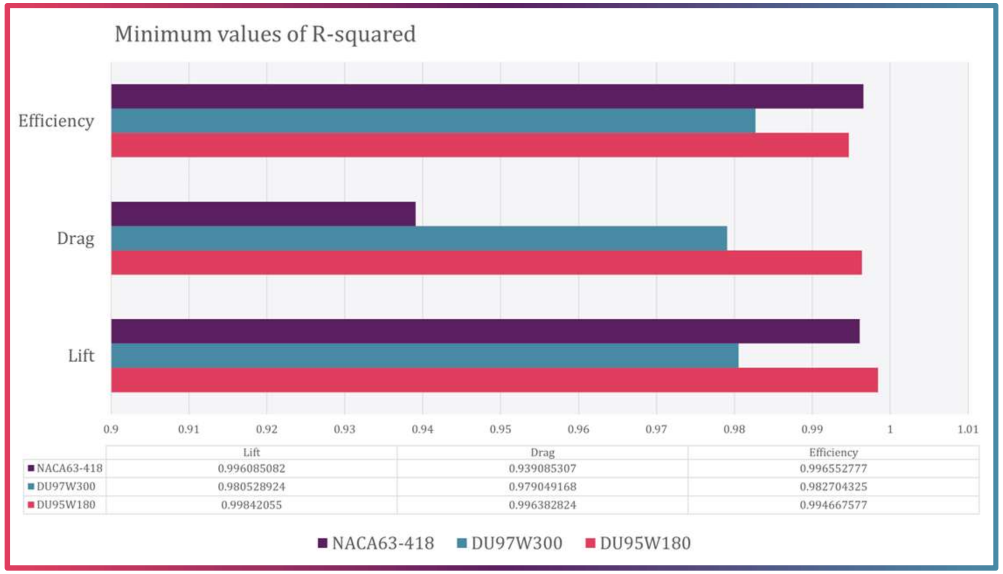
Test 1 (three airfoils used for the training are tested at different rough conditions and Reynolds numbers from the ones used to create the dataset)

Airfoil	Re (millions)	u_r	l_r	h_r	Total curves
DU95W180	7.5, 8, 10	0.1	0.1	0, 2e-4, 3.5e-4	9
DU97W300	7.5, 8, 10	0.1	0.1	0, 2.5e-4, 3.5e-4	9
NACA63-418	7, 9, 11	0.13, 0.18	0.13, 0.18	0, 2e-4, 3.5e-4	27

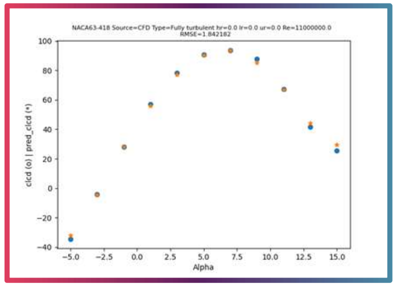
Mean

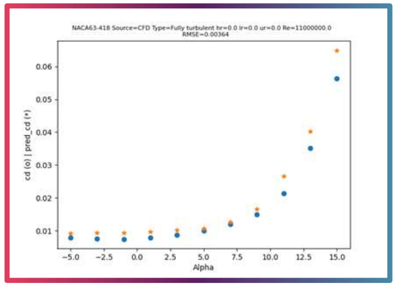


Minimun

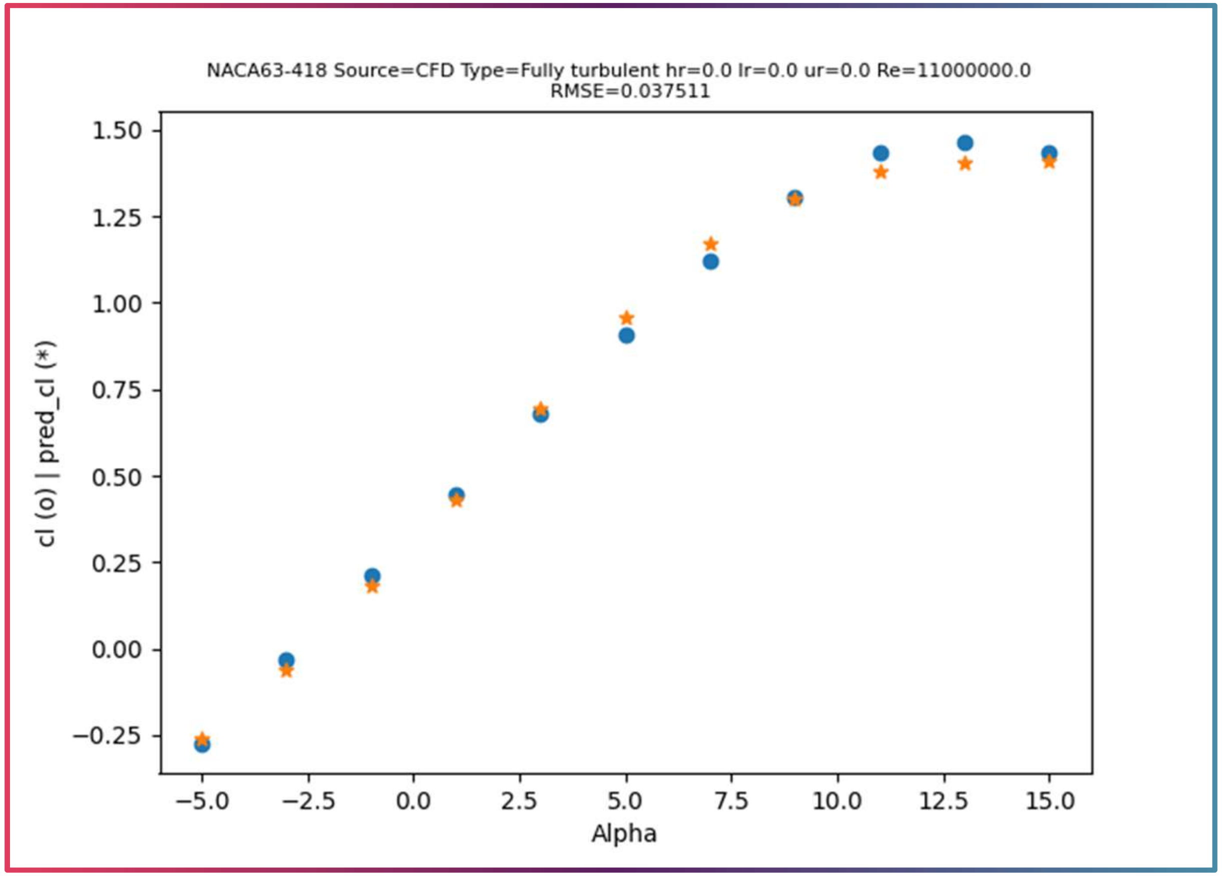


Test 1 (the worst stimation is shown and it is more than satisfactory)



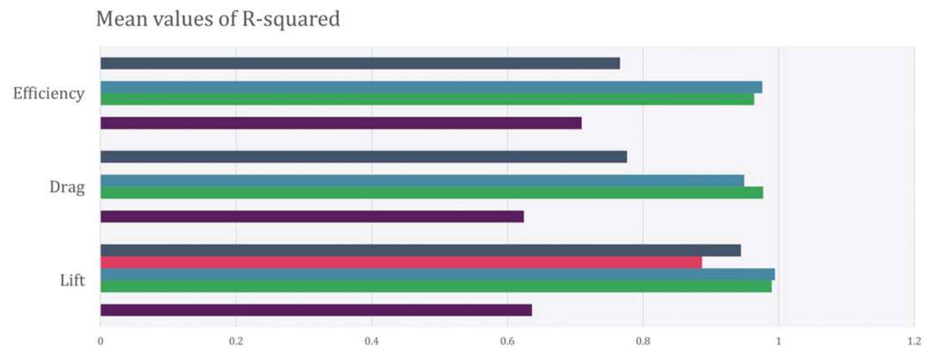


Worst stimation obtained



Test 2 (six new airfoils stimated with the roughness model)

Airfoil	Re (millions)	u_r	l_r	h_r	Total curves
FFAW3211	6	0.1, 0.2	0.2	0, 2.5e-4	3
L5T14Tunel	9	0.2	0.1, 0.15	0, 5e-4	3
S820	6, 12	0.15	0.15	0, 2.5e-4	4
ca00318bte300	9	0.2	0.2	0, 1e-4, 2.5e-4, 5e-4	4
ca00224bte300	9	0.1	0.1	0, 1e-4, 2.5e-4, 5e-4	4
FFAW3360	6	0.1, 0.2	0.1, 0.2	0, 2.5e-4	5



	Lift	Drag	Efficiency
ca00318bte300	0.94449712	0.776123217	0.766160523
ca00224bte300	0.886919666	0	0
S820	0.994294528	0.948996333	0.975770311
L5T14tunel	0.989712891	0.977125208	0.96395155
FFAW3360	0	0	0
FFAW3211	0.63625896	0.624075622	0.709308772

ca00318bte300 ca00224bte300 S820 L5T14tunel FFAW3360 FFAW3211

Poor stimations for some airfoils:

- FFAW3360 due to the high thickness
- CAs airfoils due to extreme thickness and camber
- FFAW3211: **why?**

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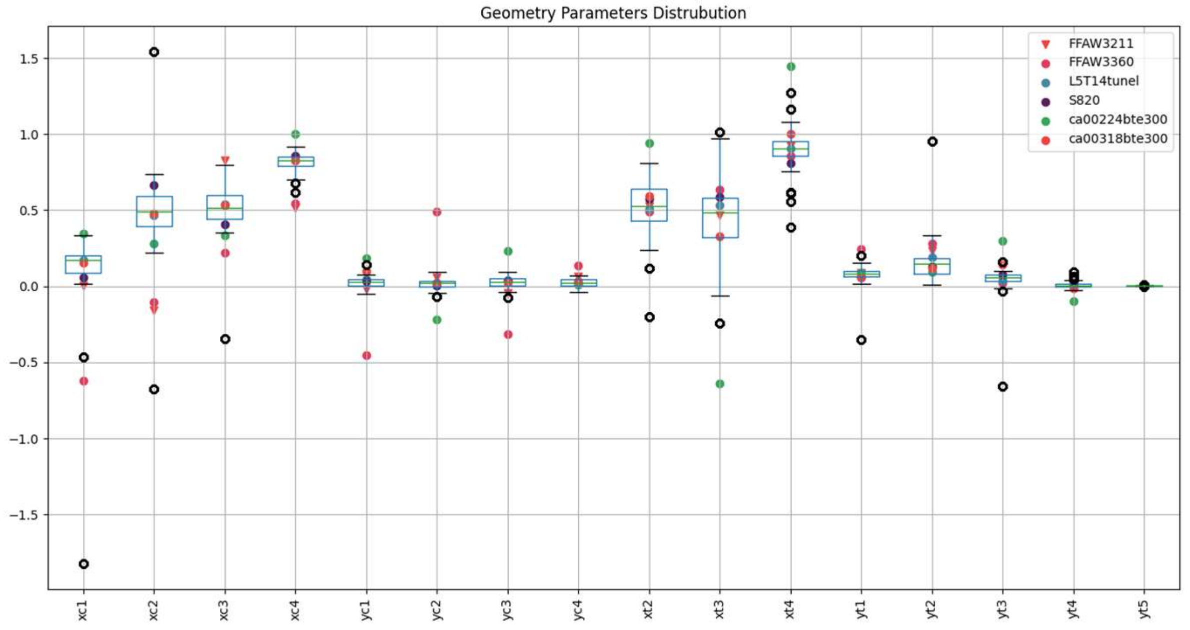
Test 2 (six new airfoils stimated with the roughness model)

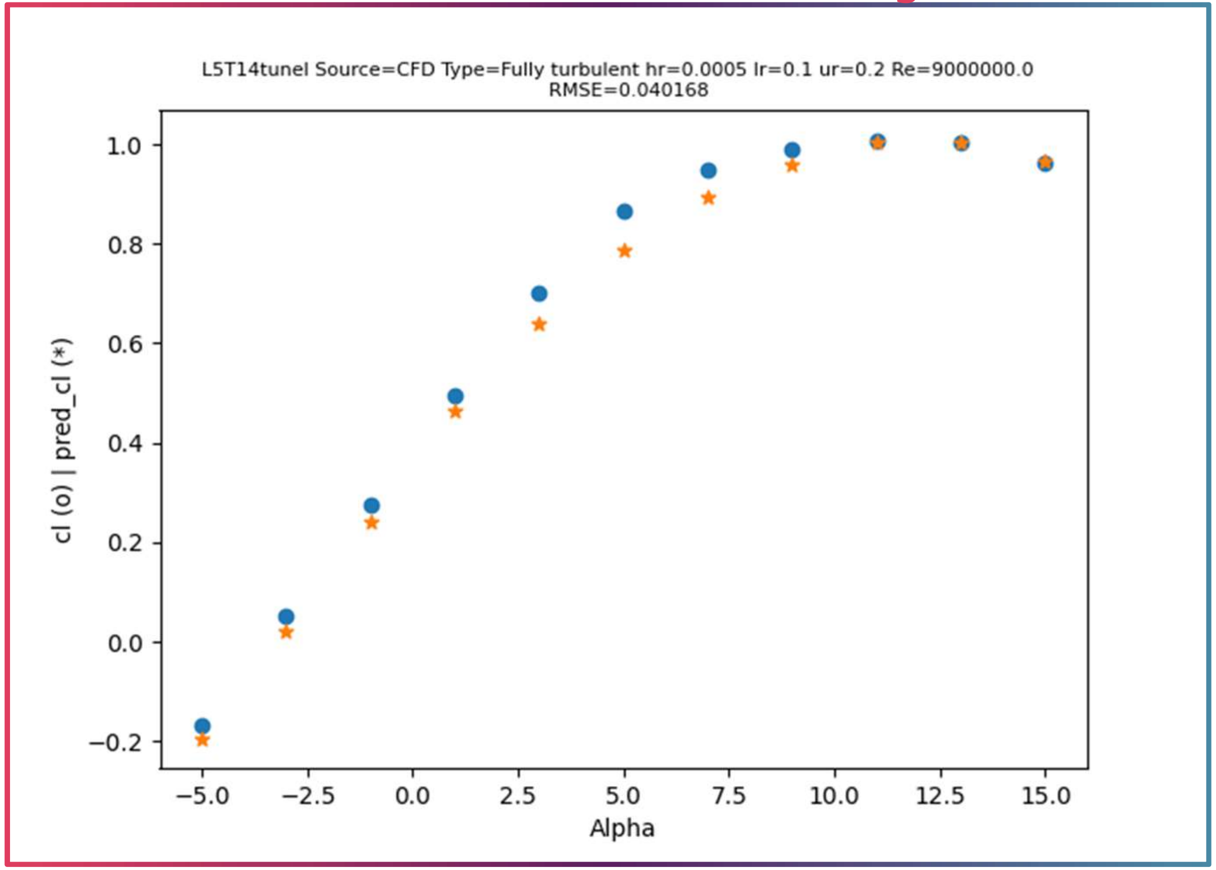


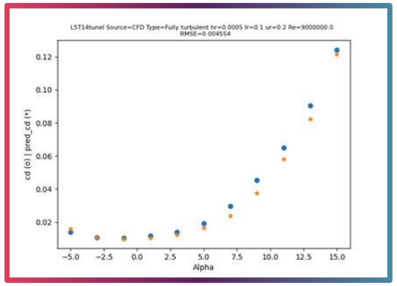
Comparing with the database statistical analysis of geometry parameters:

- FFAW3360 due to the high thickness
- CAs airfoils due to extreme thickness and camber
- FFAW3211: **is out of the wishkers of the database TRIANGLES**

Test 2 (six new airfoils stimated with the roughness model)

L5T14 good stimation considering that this airfoil was not considered inside the training dataset !





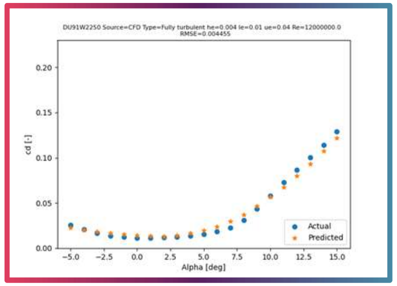
Test 3 (testing the erosion model for 26 random erosion conditions excluded from the training and validation phases)

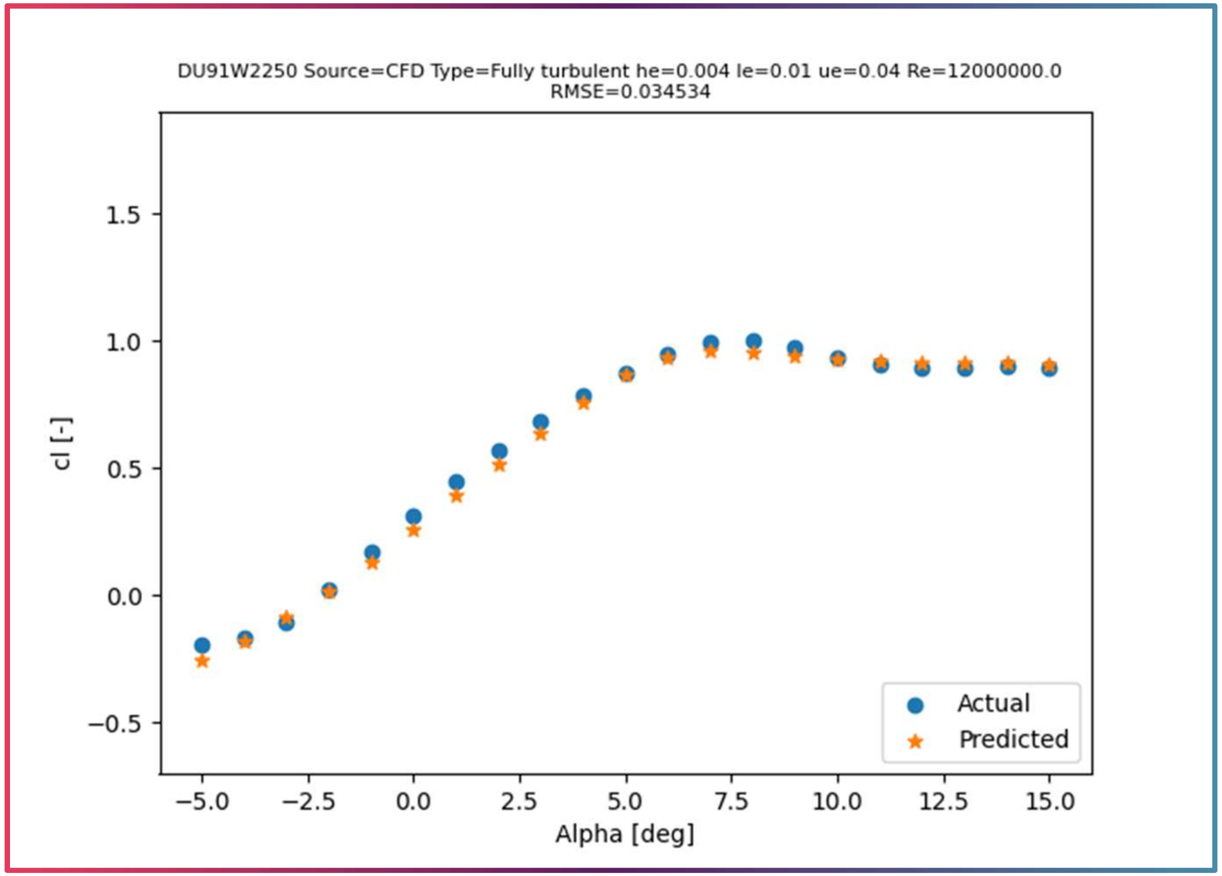
Name	he	le	ue	Re
AG25	0.001	0.04	0.02	6000000
AH79-100	0.004	0.01	0.04	9000000
B29	0.008	0.02	0.02	12000000
CLARK-YM18	0.001	0.02	0.01	6000000
DEFIANT-BL20	0.004	0.01	0.02	12000000
DFVLR-R4	0.001	0.02	0.01	6000000
DU91W2250	0.004	0.01	0.04	12000000
DU93W210	0.008	0.01	0.01	6000000
DU95W180	0.001	0.04	0.01	9000000
DU96W180	0.004	0.04	0.01	9000000
DU97W300	0.008	0.01	0.02	12000000
EPPLER1098	0.001	0.04	0.02	6000000
HUGHES-HH-02	0.004	0.02	0.02	9000000
L4T17tunel	0.008	0.02	0.04	12000000
L6T9tunel	0.001	0.02	0.01	6000000
MH93-16	0.001	0.01	0.02	9000000
MS1-0313	0.008	0.02	0.04	6000000
NACA63-418	0.004	0.02	0.02	9000000
NACA63-421	0.001	0.04	0.04	12000000
NACA64-618	0.008	0.04	0.04	6000000
RONC1046	0.001	0.01	0.01	6000000
S809	0.008	0.02	0.02	6000000
S814	0.008	0.02	0.01	12000000
S827	0.001	0.04	0.01	9000000
WB-135-35	0.004	0.02	0.04	6000000
ca00121bte300	0.008	0.01	0.01	9000000

Good agreement!

Test 3 (testing the erosion model for random erosion conditions)

Mild erosion condition





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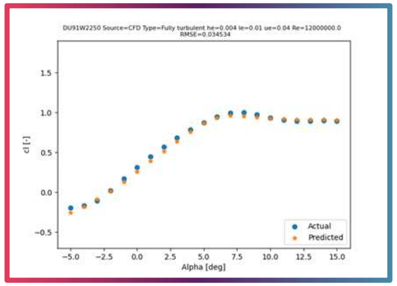
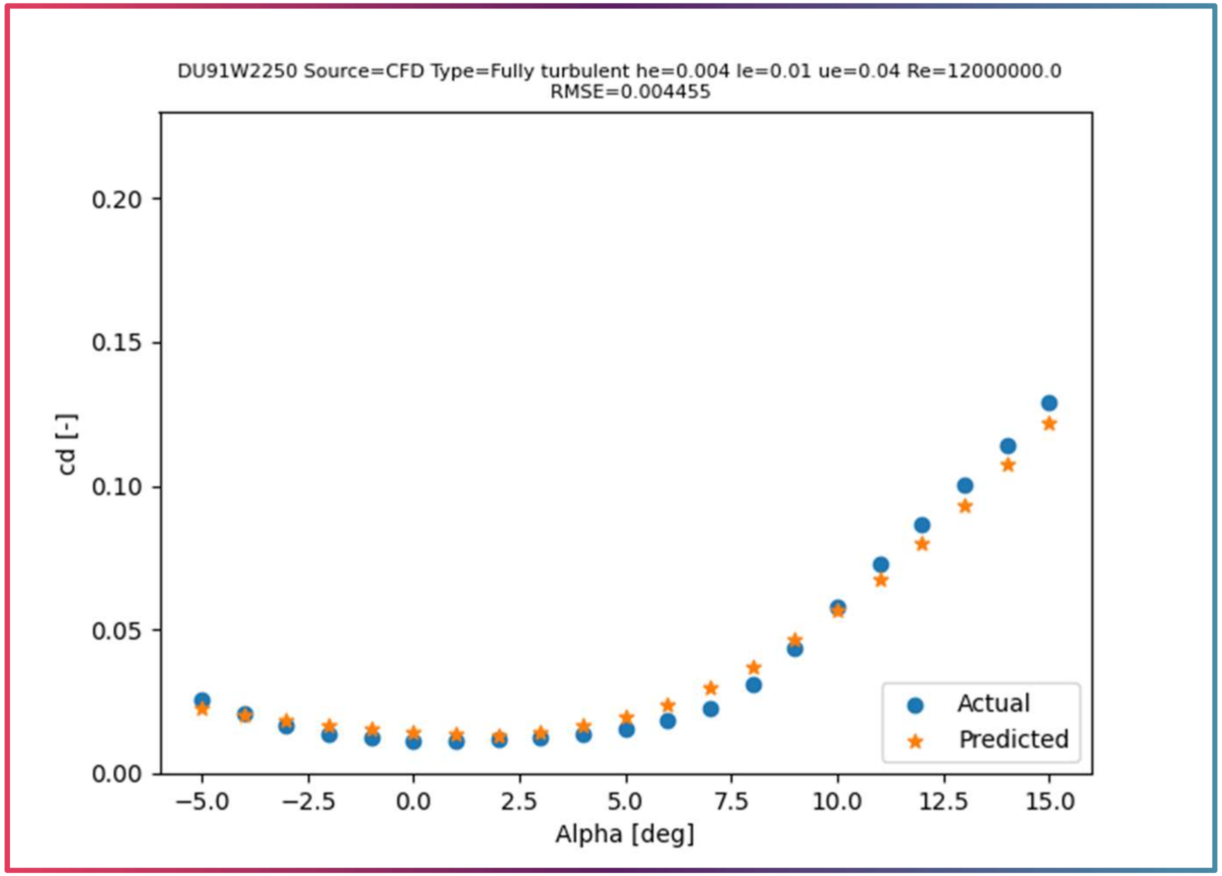
Test 3 (testing the erosion model for random erosion conditions)



Mild erosion condition



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39 airfoil considered

Neural networks perform better than random forest

6 models developed: 2 per condition, 3 per coefficient

Accurate predictions on new conditions for existing airfoil

Accurate predictions if new airfoil parameters considered within dataset range

Advanced study of the atmospheric flow integrating real climate conditions

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