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PALMO: An OVERFLOW Machine Learning Airfoil Performance Database

Version 1.0
NACA 4-Series

Dr. Jason K. Cornelius
Ames Research Center, Moffett Field, California

December 2024

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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000

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Contents

List of Figures

List of Tables

Nomenclature

BEMT	Blade Element Momentum Theory
CA	Comprehensive Analysis
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CST	Class Shape Transformations
MUAS	Micro Unmanned Aerial Systems
NACA	National Advisory Committee for Aeronautics
NASA-HECC	NASA High-End Compute Capability
PALMO	OVERFLOW Machine Learning Airfoil Performance Database
UIUC	University of Illinois at Urbana Champaign
c_l	Two-dimensional Airfoil Lift Coefficient
c_d	Two-dimensional Airfoil Drag Coefficient
c_m	Two-dimensional Airfoil Pitching Moment Coefficient

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Abstract

The OVERFLOW Machine Learning Airfoil Performance (PALMO) database has been created to enable robust modeling of airfoil performance in a variety of applications. The database uses OVERFLOW simulation data second-order accurate in time and fourth-order accurate in space with Spalart-Allmaras turbulence closure. The foundation of the in-development PALMO database is the airfoil base cube. Each base cube includes simulation data parametrized over a range of Mach numbers, Reynolds numbers, and angles-of-attack. This first release of the database includes the NACA 4-series airfoils, with parametrization in airfoil thickness and camber from an NACA 0006 to an NACA 4424. In total, 52,480 NACA 4-series calculations were run on the NASA High-End Compute Capability (HECC) supercomputer and the corresponding airfoil performance coefficients are embedded in the Appendix of this document for public distribution. This provides high-order-accurate simulation data covering a wide range of aerospace design applications, which enables users to develop OVERFLOW-quality airfoil performance look-up tables without additional high-performance computing. In addition to engineering design and analysis of aerospace vehicles, PALMO is well suited to be a benchmark dataset for the development and testing of machine learning methods in aerospace engineering. Downstream surrogate models enable OVERFLOW-quality airfoil performance predictions for any arbitrary combination of camber, thickness, Mach number, Reynolds number, and angle-of-attack within the bounds of the database.

1 Background Information

This section introduces the motivation for creating the OVERFLOW Machine Learning Airfoil Performance (PALMO) database and the expected benefits it will provide to the aerospace community. This initial release of the database contains airfoil performance coefficients from 52,480 simulations generated using the high-order accurate OVERFLOW Computational Fluid Dynamics (CFD) solver, Ref. [1]. These simulations are a parametrization of the NACA 4-series airfoil family over a wide range of Mach number, Reynolds number, and angle-of-attack values.

Although the PALMO database was conceptualized to meet a need in the rotorcraft community, it is suitable for use across fixed-wing, rotary-wing, and any other aerospace applications requiring robust airfoil performance predictions. This first release only includes NACA 4-series data, but the database may periodically be updated with additional airfoil data in future NASA TMs. The main objective of this document is to publish the PALMO database in the public domain. Future works may include example surrogate models of the database and downstream applications of those models.

1.1 Introduction and Motivation

In the aerospace community, airfoil look-up tables are often used in low- and mid-fidelity tools for the prediction of aircraft and rotorcraft performance. In the rotorcraft community, these airfoil performance look-up tables are commonly formatted as C81 tables that report airfoil performance as a function of both angle-of-attack and local Mach number. Methods such as Blade Element Momentum Theory (BEMT) and Comprehensive Analysis (CA) use C81 tables to yield fast yet meaningful results. For the fixed-wing community, the same procedure is carried out with the resulting airfoil performance look-up tables being used in downstream applications such as lifting-line tools towards aircraft design, performance analysis, flight simulation, and design optimization. In either application, obtaining accurate results requires each new wing or rotor design to have a tailored set of C81 tables with the design airfoils at appropriate Reynolds and Mach numbers. An example rotor blade airfoil table discretization is shown in Figure 1. The rotor blade is discretized into 10 stations to capture radial changes in airfoil chord, thickness, and camber. Higher discretization is especially important for modeling variable-speed rotor systems. These systems have both the rotor blade geometry and aerodynamic conditions changing as a function of radial position and rotor speed.

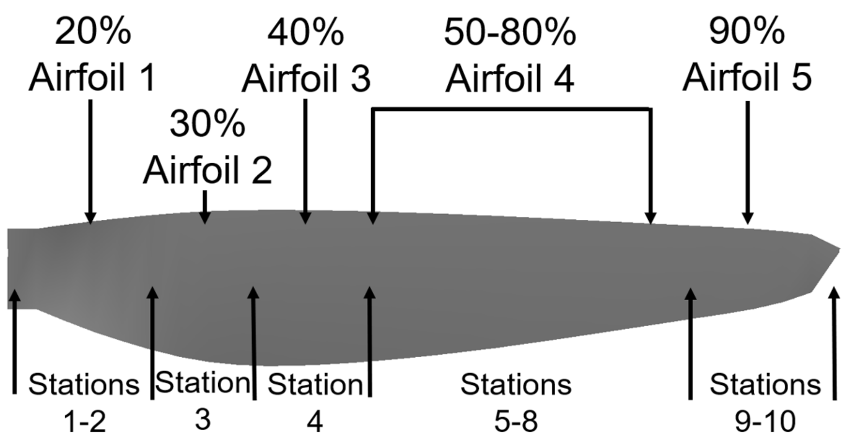

Figure 1. Airfoil Look-up Table Discretization for Variable-Speed Rotors with Large Chord Changes.

The process of creating these look-up tables is laboriously carried out by countless engineers throughout the community each year, often repeating calculations that have been done previously by other projects or teams. This work presents an airfoil performance database generated using the OVERFLOW CFD tool. Pipelines have been created to generate OVERFLOW training data on the order of tens of thousands of simulations using the NASA High-End Compute Capability (NASA-HECC), Ref. [2].

The downstream intended use of the PALMO database is surrogate modeling for fast yet accurate airfoil performance prediction. The surrogate models can be used to produce OVERFLOW quality airfoil look-up tables at user defined Mach and Reynolds numbers in fractions of a second for airfoils within the database. This enables engineers to efficiently obtain accurate airfoil performance look-up tables for new rotor geometric designs and operating conditions without high performance computing. The surrogate models are particularly well suited for applications in conceptual design and optimization, where hundreds or thousands of design variants are being analyzed.

1.2 Background on Airfoil Look-up Table Generation and Surrogate Modeling

State-of-the-art approaches for airfoil look-up table generation involve two-dimensional airfoil CFD analyses such as OVERFLOW or ARC2D, Refs. [1, 3]. These tables are sometimes created with existing experimental data but are then limited to the Mach and Reynolds numbers tested. Many experimental datasets are also proprietary, and thus not publicly accessible. Other times they are generated using lower-fidelity computational tools. The engineer must balance the need for accuracy with the computational cost and time required to create these look-up tables.

Past studies by Patt and Youngren, Ref. [4], and Cornelius et al., Refs. [5-8], document both the need for higher refinement implementations of airfoil look-up tables and the improvements obtained through their implementation. Creating these high-density tables with CFD in each iteration of conceptual design studies would be cost prohibitive. It is often this high cost that restricts their implementation to preliminary and detailed design. Conceptual designers often make simplifying assumptions as a result, such as using a set of look-up tables at constant Reynolds number even as the chord-based Reynolds number changes in successive design iterations. The alternative approach is to use fast but lower-fidelity methods such as XFOIL, Ref. [9], or the University of Illinois at Urbana Champaign (UIUC) database, Ref. [10], to update the airfoil performance tables between iterations. Given the high cost of creating CFD-based airfoil tables, there exists a growing interest in the aviation community to leverage various machine learning approaches to derive highly accurate, low-cost surrogate models for predicting airfoil performance.

Some recent studies have used neural networks to create highly efficient airfoil performance surrogate models to update the tables as the conceptual design progresses, but they have typically been based on lower-fidelity training data, Ref. [11]. Sridharan and Sinsay did apply neural networks to data from the thin-layer Navier Stokes flow solver ARC2D using the wrapper C81Gen, Ref. [12], albeit with a coarse Mach discretization and at a single Reynolds number. The use of these surrogate models for airfoil performance prediction has recently received much attention, Refs. [13-16]. Li et al. recently provided a review on this topic, Ref. [17]. These studies, however, typically rely on Class Shape Transformations (CST) such as Bernstein and Chebyshev polynomials, Refs. [18-20]. Although this process has been adopted as a popular approach for airfoil shape optimization, this parametrization of the airfoil shape introduces some discrepancies as compared to the original CFD calculations for airfoils in the training datasets.

2 PALMO 4-series Database Generation

The PALMO database was generated using the NASA High-End Compute Capability (NASA-HECC). This first version of the PALMO database has 16 base cubes, with each base cube representing a single NACA 4-series airfoil. The database currently contains 52,480 OVERFLOW simulations. Each base cube required five days of wall-clock time on sixteen 28-core Broadwell compute nodes. This resulted in a total computational cost of around 860,000 CPU hours.

The first set of airfoils included in the database are the NACA 4-series, Ref. [21]. This first-generation airfoil family was selected for the first release of the PALMO database for the following reasons:

1) ample publicly available experimental data in NASA and NACA documents, Ref. [22],
2) complete parametrization of the airfoil coordinates using just thickness and camber, and
3) relevance to a wide variety of aerospace design applications.

2.1 NACA 4-series Airfoil Family Parametrization

The foundation of the in-development PALMO methodology is the airfoil base cube, which is a high-density parametrization of OVERFLOW simulation data for a single airfoil. The data covers the ranges of Mach number, Reynolds number, and angle-of-attack reported in Table 1.

These conditions include a wide range of anticipated operating conditions from subsonic to transonic, Reynolds numbers of 75,000 to 8 million, and angle-of-attack values from -20 to +20 degrees. This is expected to bound many rotorcraft relevant applications that CFD simulation data would generally be used for. Below a Mach value of 0.25, the flow can be assumed subsonic, and thus the values from the lowest Mach in the database can be used. Below the minimum Reynolds number, which may be encountered by micro unmanned aerial systems (MUAS) or Mars helicopters, specially tailored OVERFLOW simulations beyond the scope of this work are required. For conditions in deep-stall, higher-fidelity simulations are required that are again beyond the scope of this database.

Table 1. The 3,280 Parametrized Conditions in a PALMO Base Cube.

Characteristic	Discretization
Mach Number	0.25, 0.35, 0.45, 0.55, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90
Reynolds Number	75k, 125k, 250k, 500k, 1M, 2M, 4M, 8M
Angle-of-Attack	-20 to +20, 1-degree increments

The database is expanded beyond a single base cube with the addition of airfoil parametrization. Figure 2 shows a parametrization of the NACA 4-series with variations in percent camber and thickness being added to the database. For each airfoil, all possible combinations of the Mach number, Reynolds number, and angle-of-attack from Table 1 are simulated. The database includes the symmetric 4-series airfoils as well as airfoils with two and four percent camber. The maximum percent thickness also varies from six to twenty-four percent. This allows predictions for any arbitrary combination of camber and thickness within the bounds of the training data, i.e., from an NACA 0006 to an NACA 4424.

The red stars in Figure 2 represent additional test data that was generated beyond the original 4-series parametrization. These test data were generated using the same approach in OVERLFOW but are meant to assess the accuracy of downstream surrogate models and implementations. This first release of the full PALMO 4-series database thus has 16 base cubes. The twelve cubes shown in blue with four additional test cubes, denoted by the red stars, for the NACA 3415, 3418, 4415, and 4421. All 52,480 simulations could be used directly or as training data for surrogate models. For surrogate model development and testing, the 12 blue base cubes could be used as training data while holding out some or all of the red stars for test data.

Figure 2. PALMO Database Version 1, NACA 4-series (Red stars for surrogate model testing).

2.2 Preparing the AFTGen Wrapper for OVERFLOW

The airfoil simulations are run using the AFTGen tool, Ref. [23]. AFTGen is a wrapper that handles grid generation and solution monitoring for a variety of available flow solvers. This work used AFTGen with OVERFLOW simulations second-order accurate in time and fourth-order accurate in space to develop the airfoil performance training datasets. Spalart-Allmaras turbulence closure was used, Ref. [24].

Airfoil coordinates were first generated using the XFOIL tool, which generates 4-series airfoil coordinates using the 'NACA i' command. The 'ppar' command was then used to set the number of panel nodes to XFOIL's maximum of 494 x-y coordinate pairs ('N 494'). Next the geometry design routine ('gdes') was used to create a blunt trailing edge with 0.25% trailing-edge thickness ('tgap 0.0025'). This trailing-edge gap was blended over the full length of the airfoil. All airfoil coordinate files generated using XFOIL's maximum point density are included in Appendix I.

For this work, 494 wrap-around points in the airfoil coordinate file was considered too coarse. A script was used to boost the airfoil coordinate point-density from 494 to 10,000. This was done by first transforming the XFOIL generated output into polar coordinates to 'un-wrap' the airfoil. The polar coordinates were then interpolated to boost the point-density and transformed back into x-y coordinates. The boosted CFD point-density airfoil coordinate files are also included in Appendix I.

Studies were carried out to ensure the AFTGen grid was sufficiently refined across the various operating conditions in the PALMO database. The grid point density was increased until airfoil performance predictions converged to within 1% in the linear region of the lift-curve slope following approaches documented by Cornelius et al., Ref. [7]. These studies were conducted for the NACA 0012 at all possible combinations of low Mach, high Mach, low Reynolds number, and high Reynolds number. The results from these studies are reported in Tables 2-4 for convergence of normal, periodic, and trailing-edge grid cells, respectively. Table 5 reports convergence on the number of chord lengths to the simulation boundary (200 chord lengths). The PALMO database grid settings are reported in Table 6, and yielded approximately 325,000 cells.

Table 2. NACA 0012 Normal Cell Grid Convergence, Periodic Cells-=401, Trailing-edge Cells=41.

Reynolds Number		125k						4M					
Mach Number		0.3			0.7			0.3			0.7		
Normal Cells		401	501	601	401	501	601	401	501	601	401	501	601
c_l	0	0.0005	0.0005	0.0005	0.0007	0.0007	0.0007	-0.0002	-0.0002	-0.0002	-0.0001	-0.0001	-0.0001
	5	0.5420	0.5423	0.5424	0.5797	0.5820	0.5800	0.5794	0.5778	0.5764	0.6810	0.6827	0.6838
	10	0.9818	0.9743	0.9862	0.5877	0.5893	0.5887	1.1143	1.1168	1.1170	0.6187	0.6181	0.6193
c_d	0	0.0163	0.0162	0.0161	0.0176	0.0175	0.0175	0.0093	0.0093	0.0092	0.0098	0.0097	0.0097
	5	0.0196	0.0195	0.0194	0.0452	0.0452	0.0450	0.0109	0.0108	0.0108	0.0413	0.0414	0.0414
	10	0.0367	0.0365	0.0362	0.1303	0.1311	0.1303	0.0174	0.0173	0.0172	0.1259	0.1264	0.1263
c_m	0	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
	5	0.0049	0.0049	0.0049	0.0175	0.0173	0.0177	0.0011	0.0013	0.0015	0.0190	0.0189	0.0188
	10	0.0159	0.0158	0.0158	-0.0271	-0.0280	-0.0272	0.0091	0.0088	0.0087	-0.0295	-0.0303	-0.0301

Table 3. NACA 0012 Periodic Cell Grid Convergence, Normal Cells=501, Trailing-edge Cells=41.

Reynolds Number		125k						4M					
Mach Number		0.3			0.7			0.3			0.7		
Periodic Cells		301	401	501	301	401	501	301	401	501	301	401	501
c_l	0	0.0004	0.0005	0.0006	0.0007	0.0007	0.0007	-0.0002	-0.0002	-0.0002	0.0001	-0.0001	-0.0001
	5	0.5417	0.5423	0.5424	0.5720	0.5820	0.5824	0.5763	0.5778	0.5780	0.6730	0.6827	0.6842
	10	0.9802	0.9743	0.9853	0.5858	0.5893	0.5898	1.1089	1.1168	1.1186	0.6165	0.6181	0.6192
c_d	0	0.0163	0.0162	0.0162	0.0176	0.0175	0.0175	0.0093	0.0093	0.0092	0.0098	0.0097	0.0097
	5	0.0196	0.0195	0.0195	0.0448	0.0452	0.0451	0.0110	0.0108	0.0108	0.0401	0.0414	0.0415
	10	0.0370	0.0365	0.0363	0.1300	0.1311	0.1308	0.0180	0.0173	0.0171	0.1256	0.1264	0.1262
c_m	0	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
	5	0.0050	0.0049	0.0049	0.0178	0.0173	0.0177	0.0015	0.0013	0.0013	0.0225	0.0189	0.0191
	10	0.0159	0.0158	0.0158	-0.0267	-0.0280	-0.0277	0.0096	0.0088	0.0086	-0.0290	-0.0303	-0.0299

Table 4. NACA 0012 Trailing-edge Cell Grid Convergence, Normal Cells=501, Periodic Cells=401.

Reynolds Number		125k						4M					
Mach Number		0.3			0.7			0.3			0.7		
Trailing Edge Cells		31	41	51	31	41	51	31	41	51	31	41	51
c_l	0	0.0006	0.0005	0.0005	0.0007	0.0007	0.0006	-0.0001	-0.0002	-0.0002	0.0001	-0.0001	-0.0002
	5	0.5430	0.5423	0.5417	0.5839	0.5820	0.5766	0.5790	0.5778	0.5768	0.6842	0.6827	0.6816
	10	0.9880	0.9743	0.9716	0.5931	0.5893	0.5869	1.1200	1.1168	1.1144	0.6218	0.6181	0.6164
c_d	0	0.0162	0.0162	0.0161	0.0176	0.0175	0.0175	0.0093	0.0093	0.0092	0.0097	0.0097	0.0097
	5	0.0196	0.0195	0.0195	0.0455	0.0452	0.0447	0.0109	0.0108	0.0108	0.0416	0.0414	0.0412
	10	0.0366	0.0365	0.0363	0.1319	0.1311	0.1306	0.0174	0.0173	0.0172	0.1271	0.1264	0.1255
c_m	0	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0001
	5	0.0048	0.0049	0.0050	0.0169	0.0173	0.0182	0.0011	0.0013	0.0016	0.0185	0.0189	0.0192
	10	0.0152	0.0158	0.0163	-0.0287	-0.0280	-0.0274	0.0081	0.0088	0.0092	-0.0309	-0.0303	-0.0293

Table 5. NACA 0012 Chord Lengths to Boundary Convergence, Normal Cells=601, Periodic Cells=501, Training Edge Cells=41.

Reynolds Number		125k					
Mach Number		0.3			0.7		
Trailing Edge Cells		50	100	200	50	100	200
c_l	0	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007
	5	0.5425	0.5457	0.5459	0.5828	0.5831	0.5831
	10	0.9867	0.9878	0.9878	0.5905	0.5899	0.5915
c_d	0	0.0161	0.0162	0.0162	0.0174	0.0174	0.0175
	5	0.0194	0.0193	0.0193	0.0451	0.0452	0.0453
	10	0.0361	0.0359	0.0359	0.1311	0.1307	0.1321
c_m	0	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
	5	0.0049	0.0047	0.0048	0.0177	0.0176	0.0175
	10	0.0158	0.0158	0.0158	-0.0280	-0.0276	-0.0288

Table 6. High Point Density OVERFLOW Airfoil Grid Settings: 325,000 cells.

Grid Setting Parameter	Value
Normal Cells	601
Periodic Cells	501
Trailing-edge Cells	41
Chord Lengths to Boundary	200

3 Summary

The OVERFLOW Machine Learning Airfoil Performance (PALMO) database has been created to aid engineers in the design and analysis of aerospace vehicles. This first release of the database contains 52,480 simulations parametrizing the NACA 4-series airfoil family over ranges of Mach number, Reynolds number, and angle-of-attack values relevant to a wide range of aerospace problems. PALMO is relevant to rotorcraft, fixed-wing, and a variety of other aerospace applications. This work aims to increase access to accurate airfoil performance predictions without the need for high performance computing. In addition to engineering design and analysis of aerospace vehicles, PALMO is well suited to be a benchmark dataset for the development and testing of machine learning methods in aerospace engineering.

Future version releases expanding the database may be published in future NASA TMs.

Appendix I contains the airfoil coordinate files used in AFTGen. The original XFOIL coordinate files and the boosted CFD point density coordinate files are included.

Appendix II has three files with the PALMO database airfoil performance coefficients. There is one for each of airfoil lift, drag, and pitching moment coefficient as a function of the input variables (Mach number, Reynolds number, angle-of-attack, 4-series section thickness, and 4-series section camber).

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Appendix I: Airfoil Coordinate Files

Training Airfoil Data (Rectangular Grid of NACA 4-series parametrized camber and thickness)

1. NACA 0006
    a. Maximum XFOIL Point Density: NACA_0006_XFoil.txt
    b. Boosted CFD Point Density: NACA_0006_CFD.txt
2. NACA 0012
    a. Maximum XFOIL Point Density: NACA_0012_XFoil.txt
    b. Boosted CFD Point Density: NACA_0012_CFD.txt
3. NACA 0018
    a. Maximum XFOIL Point Density: NACA_0018_XFoil.txt
    b. Boosted CFD Point Density: NACA_0018_CFD.txt
4. NACA 0024
    a. Maximum XFOIL Point Density: NACA_0024_XFoil.txt
    b. Boosted CFD Point Density: NACA_0024_CFD.txt
5. NACA 2406
    a. Maximum XFOIL Point Density: NACA_2406_XFoil.txt
    b. Boosted CFD Point Density: NACA_2406_CFD.txt
6. NACA 2412
    a. Maximum XFOIL Point Density: NACA_2412_XFoil.txt
    b. Boosted CFD Point Density: NACA_2412_CFD.txt
7. NACA 2418
    a. Maximum XFOIL Point Density: NACA_2418_XFoil.txt
    b. Boosted CFD Point Density: NACA_2418_CFD.txt
8. NACA 2424
    a. Maximum XFOIL Point Density: NACA_2424_XFoil.txt
    b. Boosted CFD Point Density: NACA_2424_CFD.txt
9. NACA 4406
    a. Maximum XFOIL Point Density: NACA_4406_XFoil.txt
    b. Boosted CFD Point Density: NACA_4406_CFD.txt
        i. Note* This airfoil did not converge with the point density script. CFD file is ready for input into OVERFLOW or ARC2D, but at original XFOIL density.

10. NACA 4412
    a. Maximum XFOIL Point Density: NACA_4412_XFoil.txt
    b. Boosted CFD Point Density: NACA_4412_CFD.txt
11. NACA 4418
    a. Maximum XFOIL Point Density: NACA_4418_XFoil.txt
    b. Boosted CFD Point Density: NACA_4418_CFD.txt
12. NACA 4424
    a. Maximum XFOIL Point Density: NACA_4424_XFoil.txt
    b. Boosted CFD Point Density: NACA_4424_CFD.txt

Testing Airfoil Data (Off-axis NACA 4-series airfoils)

13. NACA 3415
    a. Maximum XFOIL Point Density: NACA_3415_XFoil.txt
    b. Boosted CFD Point Density: NACA_3415_CFD.txt
14. NACA 3418
    a. Maximum XFOIL Point Density: NACA_3418_XFoil.txt
    b. Boosted CFD Point Density: NACA_3418_CFD.txt
15. NACA 4415
    a. Maximum XFOIL Point Density: NACA_4415_XFoil.txt
    b. Boosted CFD Point Density: NACA_4415_CFD.txt
16. NACA 4421
    a. Maximum XFOIL Point Density: NACA_4421_XFoil.txt
    b. Boosted CFD Point Density: NACA_4421_CFD.txt

Appendix II: PALMO Database Release, Version 1

1. PALMO 4-series Database Lift Coefficient: PALMO_NACA_4_series_cl.txt
2. PALMO 4-series Database Drag Coefficient: PALMO_NACA_4_series_cd.txt
3. PALMO 4-series Database Pitching Moment Coefficient: PALMO_NACA_4_series_cm.txt