IRPWind

Integrated Research Programme
on Wind Energy

2nd Call for Joint Experiments

2D AIRFOIL UNSTEADY AERODYNAMICS OPEN DATA SET

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Definitions/Acronyms

EXECUTIVE SUMMARY

A selection of four different unsteady aerodynamic experiments have been done to prepare a database which will serve for the analysis, investigation and tool validation of airfoil unsteady behavior of wind turbine blades.

A selection of reliable data has been performed and they have been published in an open access repository together with the needed scripts and information for interpretation and data use for validation.

Some model benchmarking exercises have also been prepared in the Windbench platform, providing a free 'Sandbox' service where data and scripts can also be accessible in a fully functional environment.

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1. Introduction

The wind energy sector is extensively employing aeroelastic simulations for design, evaluation and certification of wind turbines in different environments and operating conditions. For an accurate modeling, the aeroelastic models and tools used should be properly validated against reliable experimental data. However, there is a lack of high-quality open-access databases for aerodynamic or aeroelastic investigations related to wind turbine performance.

This project has compiled data from among the best worldwide unsteady aerodynamic experiments, selecting sets of data that can be applied to the wind turbine aeroelastic investigation works. These selected data have been organized, published in an open access server and in a validation platform where different work benches can be used for validation exercise.

Description of the experiments, the data and the publishing platforms are presented in this document.

2. Data selection

Four different experiments are feeding this data base:

a. University of Glasgow dynamic stall experiments

   The University of Glasgow Department of Aerospace Engineering performed extensive dynamic stall tests during the 1980s and 1990s. Fourteen different airfoils were tested at a wide variety of pitching motion conditions at their 7ft x 5ft section wind tunnel "Hanley Page Tunnel".

b. NREL OSU experiments

   The US National Renewable Energy Laboratory (NREL) during the 1990s awarded a contract to Ohio State University (OSU) to perform a wind tunnel test program where up to thirteen airfoils were tested at steady and unsteady angles of attack.

c. CENER unsteady airfoil pitching and flapping tests at DTU

   The National Renewable Energy Center of Spain (CENER), within the frame of the EU funded project 'Windtrust', performed on 2015 an extensive wind tunnel test over the NACA64_3-418 airfoil with different types of unsteady pitch and flap motions for aeroelastic tool validation purpose.

d. ForWind airfoil tests under tailored inflow turbulence

   The joint Center for Wind Energy Research of the Universities of Oldenburg, Hannover and Bremen (ForWind), within the EU funded project 'AVATAR', performed a very specific experiment at the acoustic wind tunnel of the University of Oldenburg where the DU00-W-212 airfoil was tested under specifically tailored turbulence inflow patterns.

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2.1 Data selected for the data base

From all the data available in these experiments, a preliminary selection has been made to be included in the open data set. The selection has taken into account to present in first instance homogenous type of tests to help on the comparison and validation work. In this way, the sinusoidal type of motion has been chosen. From the great variety of airfoils tested at the University of Glasgow and NREL tests, only a few have been incorporated that have more relation with the wind energy sector.

The data set is made in a way that can be later completed with more data from these tests or from different tests that could be performed in the future.

This is a brief description of the data selected from the four experiments for the data set:

- University of Glasgow experiments:
  NACA0015 and NACA0030 airfoils tested at sinusoidal type motion of the pitch.
- NREL experiments:
  LS(1)0417MOD, NACA4415 and S809 airfoils tested at sinusoidal type motion of the pitch.
- CENER experiments:
  NACA643-418 airfoil tested at sinusoidal type motion of the pitch, the flap and combined pitch and flap.
- University of Oldenburg experiments:
  DU00W212 airfoil with laminar flow, open grid condition and one sinusoidal dynamic grid condition.

3. Description of the experiments

In this chapter the four experiments are explained, including brief description of the facility and the instrumentation used.

3.1 University of Glasgow experiments description

These 2-D dynamic stall tests were conducted by the Department of Aerospace Engineering, University of Glasgow, Glasgow, UK, in the 1980s and 1990s.

3.1.1 Site Description:

All the tests were conducted in the University of Glasgow "The Hanley Page Tunnel" with a test section 7ft x 5ft (2.1m x 1.5m). Maximum speed 120mph (55m/s). Both NACA 0015 and NACA 0030 2D dynamic stall models were built with a chord length of c = 0.55m, and they spanned the shorter dimension of the tunnel (1.5 m.). Their construction was of a fiber glass skin bonded to a steel or aluminum spar. A hydraulically actuated crank and pitch link mechanism was used to pitch each airfoil model about its quarter chord, with pitch angle feedback provided by a rotational displacement transducer.

Figure 1. Test section view of Glasgow Hanley Page Tunnel

3.1.2 Instrumentation:

Each model was instrumented with high performance Kulite or Entran surface mounted pressure transducers at the model centre-span; models for 2-D dynamic stall contained 30 transducers arranged in a chordwise manner on the airfoil upper and lower surfaces. Pressure transducer signals were anti-aliased filtered and amplified before simultaneous sampling across all the transducers on the model.

Unsteady and dynamic stall pressure measurements were acquired and post processed resulting in force coefficients measured exclusively from the pressure taps, with no wake rake measurements of drag. Therefore the data available are Cl, Cdp (only the pressure drag, not the total drag) and Cm for the range of angle of attack excursions. During these tests data acquisition used a DEC MINC limited to a sampling rate of around 550 samples per second per channel for 256 samples. As part of the standard testing protocol sinusoidal oscillatory tests were sampled over ten pitch cycle oscillations after five previous cycles had been completed. Accurate sampling triggering ensured that an averaging calculation across the sampling cycles could be performed without loss of the details of the time varying aerodynamic transients.

3.1.3 Measurement Campaign:

For dynamic stall tests the wind tunnel was run usually at a nominal free stream speed of U_∞ = 42m/s giving a chord Reynolds number of 1.5 million for a 0.55m chord, and a Mach number below 0.16. For all the testing conditions the turbulence intensity level of the flow was always below 0.5%.

The models were tested over a range of test and motion types. Here only are included the sinusoidal tests that were performed at a range of mean angles and amplitudes over a range of reduced frequencies $k = \omega c/U_\infty$,where $\omega = 2\Pi f$ and f is the oscillation frequency in Hz.

For static tests the model was held at fixed angle of attack and the unsteady pressure data sampled.

The complete data from these experiments can be downloaded from: http://dx.doi.org/10.5525/gla.researchdata.464 . Further information can be found at [1].

3.2 NREL experiments description

The National Renewable Energy Laboratory (NREL), funded by the US Department of Energy, awarded a contract to Ohio State University (OSU) to conduct the dynamic stall wind tunnel tests on different airfoils during the 1990s.

3.2.1 Site description:

The OSU ARC (Aerospace Research Center) Battelle Subsonic Wind Tunnel is an open circuit wind tunnel with a 0.91 × 1.52 m. (3 × 5 ft) test section. The length of the test section is 2.4 m. The maximum tunnel wind speed is 45 m/s, produced by a 2.44 m. diameter, 6-bladed fan located at the exit. The fan is powered by a 93.2 kW, 3-phase AC motor. Test section turbulence level measures below 0.1%.

2D models of the S809, the LS(1)0417MOD and the NACA 4415 airfoils among others, with constant chord of 457 mm. were manufactured out of a sandwiched composite skin over ribs. The main load bearing member was a 38-mm diameter steel tube which passed through the model quarter chord station. Ribs and end plates were used to transfer loads from the composite skin to the steel tube. The final surface was hand worked using templates to attain given coordinates within a required tolerance of ±0.25 mm.

To minimize pressure response time, which is important for the unsteady testing, the surface pressure tap lead-out lines had to be as short as possible. Consequently, a compartment was built into the model so pressure scanning modules could be installed inside the model. This compartment was accessed through a panel door fitted flush with the model contour on the lower (pressure) surface.

3.2.2 Instrumentation:

Data were acquired and processed from 60 surface pressure taps, four individual tunnel pressure transducers, an angle of attack potentiometer, a wake probe position potentiometer, and a tunnel thermocouple. The data acquisition system included an IBM PC-compatible, 80486-based computer connected to a Pressure Systems Incorporated (PSI) data scanning system. The PSI system included a 780B Data Acquisition and Control Unit (DACU), 780B Pressure Calibration Unit (PCU), 81-IFC scanning module interface, two 2.5-psid pressure scanning modules (ESPs), one 20-inch water column range pressure scanning module, and a 30-channel Remotely Addressed Millivolt Module (RAMM-30).

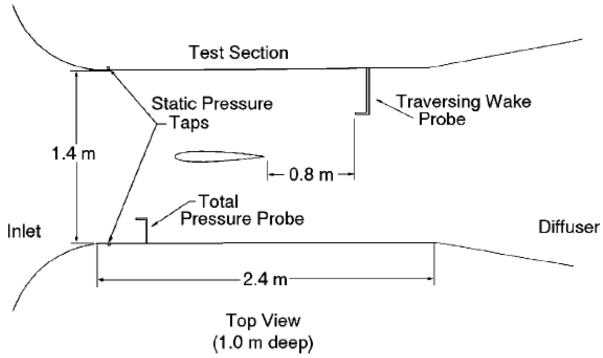

Figure 2. Sketch of test section arrangement at OSU (3 x 5) wind tunnel

3.2.3 Measurement Campaign:

Tests were performed at Reynolds numbers of 0.75, 1, 1.25 and 1.5 million.

Data were obtained at surface clean condition of the airfoils and also applying Leading Edge Grit Roughness (LEGR). This data base only has data from the clean condition cases.

For steady state cases, the model was set to angle of attack and the tunnel conditions were adjusted. At operator request, pressure measurements from the airfoil surface taps and all other channels of information were acquired and stored by the DACU and subsequently passed to the controlling computer for final processing. The angles of attack were always set in the same progression, from negative to positive values.

For model oscillating cases, the tunnel conditions were set while the model was stationary at the desired mean angle of attack. The "shaker" was started, after approximately 10 seconds the model surface pressure and tunnel condition data were acquired. Generally, 120 data scans were acquired over three model oscillation cycles. Since surface pressures were scanned sequentially, the data rate was set so the model rotated through less than 0.50° during any data burst.

The pitch oscillations data were acquired at frequencies of 0.6, 1.2, and 1.8 Hz. Two sine wave forcing functions were used, ±5.5° and ±10°, at mean angles of attack of 8°, 14°, and 20°.

For model oscillating cases, the model surface pressure measurements were acquired and post processed resulting in force coefficients, with no wake rake measurements of drag. Therefore the data available are Cl, Cdp (only the pressure drag, not the total drag) and Cm for the range of angle of attack excursions. For the steady state cases, wake pressure data were acquired from a traversed pitot-static probe. These pressure measurements were used to calculate drag coefficient. But these drag coefficients data are not compiled in this data set, only the pressure drag data are presented.

The complete data from these experiments can be downloaded from: https://wind.nrel.gov/airfoils/OSU_data/. Further information can be found at [2], [3] and [4].

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3.3 CENER experiment description

These experiments took place during two campaigns performed at May and November 2015 within the EU funded project 'Windtrust' under FP7 with Grant agreement number: 322449.

3.3.1 Site Description

The wind tunnel tests have been performed at the 'red' wind tunnel facility of DTU Wind Energy Department at Lyngby Campus.

This is an open loop suction wind tunnel with a contraction ratio of 12.5:1. The test section has a cross section of 0.5 m x 0.5 m and length of 1.3 m, and a maximum wind speed of 60 m/s. The main dimensions of the wind tunnel are shown in the figure below.

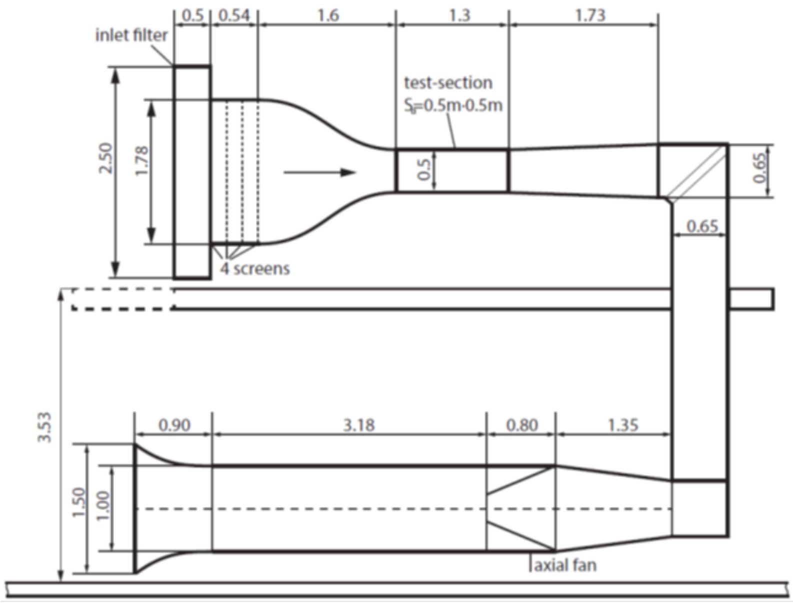

Figure 3. DTU 'RED' open loop wind tunnel scheme

The quality of the flow is increased through an inlet filter and four screens placed before the contraction. The turbulence intensity is about TI = 0.08-0.07.

The inflow is from the upper left side and the velocity of the flow is measured by a pitot tube just after the inlet (head of the probe at 0.07 meters from the test section inlet) and 0.10 m from the wall, as shown in figure below.

The model is placed vertically in the test section spanning from bottom and top walls. The model hinge point is located 0.61 m. from the test section inlet.

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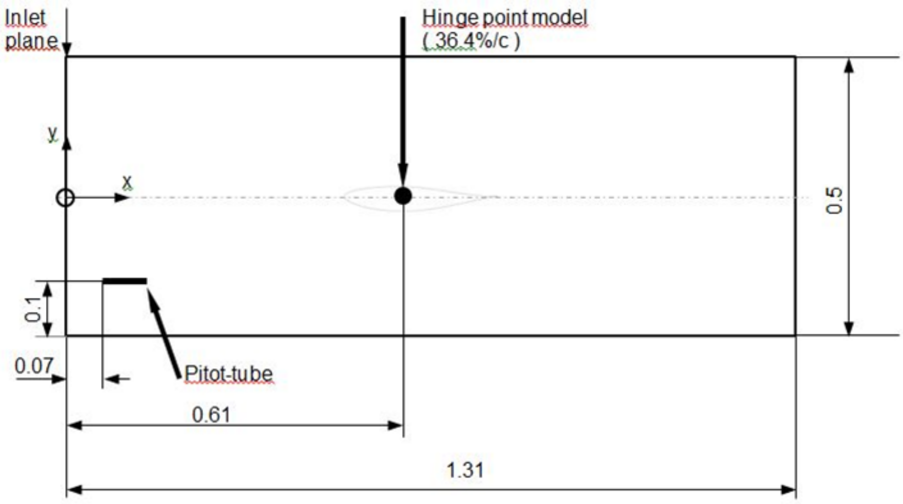

Figure 4. Test section plan view

A wind tunnel model wing representing the NACA643-418 airfoil has been used for this test. It has a chord of c=0.25 m. and a span of l=0.5 m. Surface of the model is made of carbon-fiber-reinforced plastic molded to the subscribed shape and supported by a mechanical frame made out of six aluminum ribs.

The model has been designed to have a flexible trailing edge flap, by using thinner fiber sections in the surface at the bending positions for a continuous airfoil surface. The aim is to have a 15% flap for a wing chord section of 250 mm., i.e., 37.5 mm. The flap actuation was provided through a linear motor that moves a rudder horn on the pressure side and in the half span of the model (see sketch below).

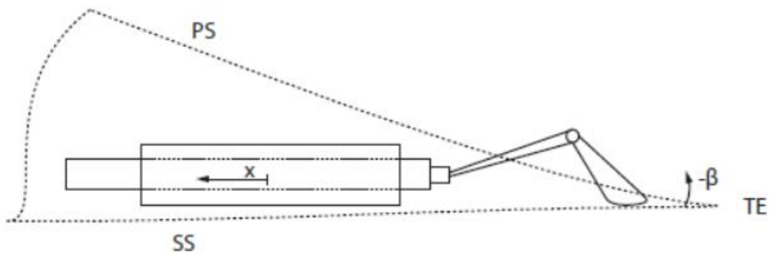

Figure 5. Flap linear motor actuator system

When the flap is moved to different angular positions, the carbon fiber shell of the flap on the pressure side slides into the undeflected wing shell. The pressure side of the flap is deflected linearly. However, the flap shell on the suction side is bended, as shown in Figure 6.

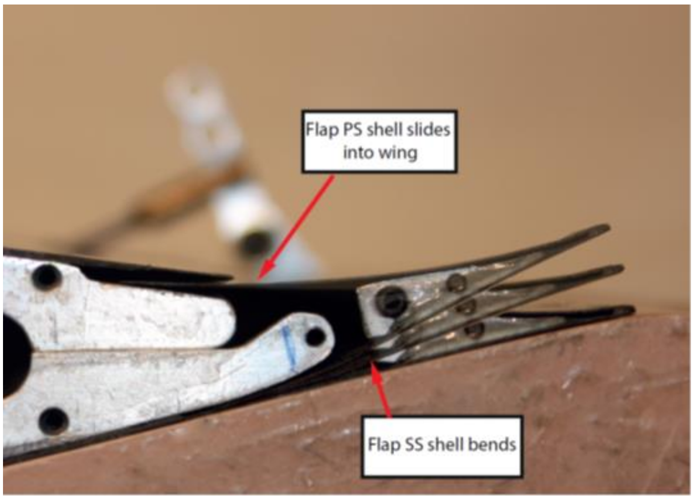

Figure 6. Model flap deflection scheme

3.3.2 Instrumentation

Model is instrumented with 63 pressure taps in line at span section 41% and connected to two 32 channel pressure transducers. The other remaining channel was used for the test section pitot tube. The static pressure from the pitot tube is used as reference pressure.

Lift , Pitching Moment and Pressure Drag Coefficients were calculated by integration of the pressure distribution over the airfoil.

3.3.3 Measurement Campaign

All the tests have been performed at a Reynolds number of 0.5 million (wind tunnel speed: 30 m/s). The four types of tests included in this data base are:

- Baseline static polars:

  Measurements at steady conditions are taken (AoA and Flap are not moving).

  Different Flap deflections are taken (-10^0, -5^0, 0^0, 5^0 & 10^0). For each Flap angle, different angles of attack are measured in the same run. The measuring time at one fixed angle of attack is 10 seconds.

- AoA sinusoidal movements (pitch motion):

  The angle of attack is moved with a sinusoidal movement. Flap is fixed.

- Flap sinusoidal movements:

  The flap is moved with a sinusoidal movement. AoA is fixed.

- AoA & Flap combined sinusoidal movement

  Angle of attack and flap are moved with a sinusoidal motion. Both have the same frequency but can have different phase delays between them.

3.4 University of Oldenburg experiments description

Experimental airfoil characterizations with different inflow conditions were performed on a DU00-W-212 model in the return-type acoustic wind tunnel at the University of Oldenburg during 2015 and 2016 for the EU funded project 'AVATAR' with grant agreement nº: 608396.

3.4.1 Site description:

The model representing the DU00-W-212 airfoil has a chord of 300 mm and is vertically mounted inside the closed test section with cross-section of 1.0 m x 0.805 m (w x h) and 2.6 m length. The model spans the complete height of the test section (805 mm.) and is fixed to two rotating plates at its ends, which are fitted flush with the test section floor and ceiling. Two axes support the model at quarter chord and each axis is connected to a three-component load cell. The top axis is also equipped with a torque sensor and a stepper motor to control the geometric angle of attack, which is monitored by an angle encoder at the bottom mount.

The reference wind speed is measured with a Setra C239 pressure gauge connected to Pitot-static tubes in the wind tunnel contraction. A combined sensor for the meteorological data (ambient pressure p, temperature T, rel. humidity rH) is located downstream the airfoil at the end of the closed test section.

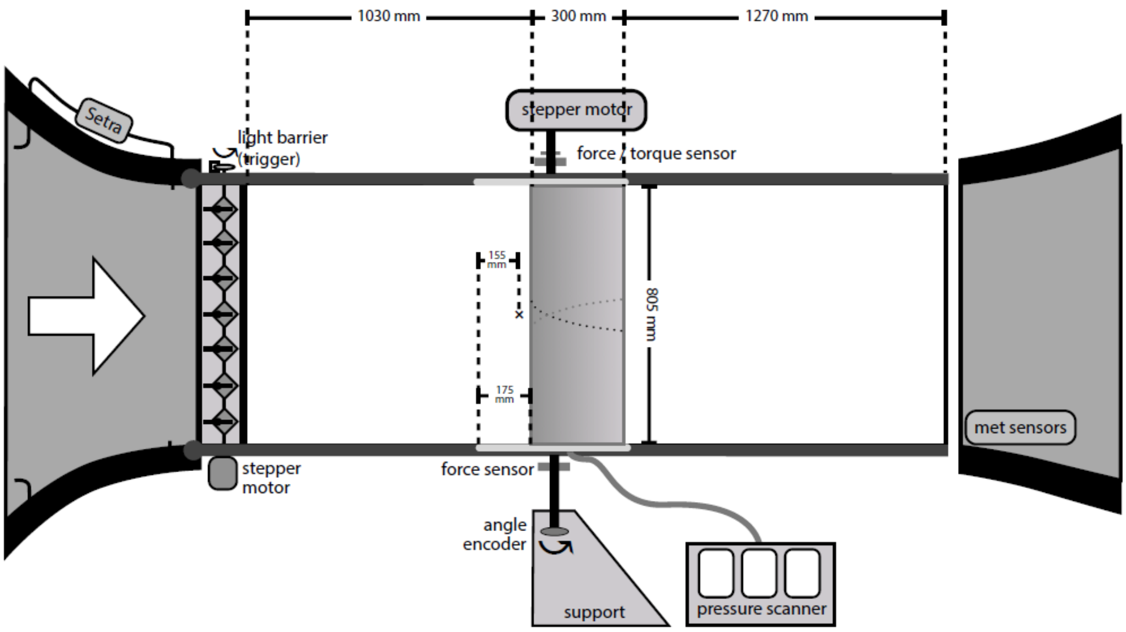

Figure 7. University of Oldenburg experiment set up view

An active grid was inserted between nozzle and test section in order to generate the reproducible, customized inflow patterns for the turbulent measurements. The grid features 16 individually movable shafts with attached flaps, of which only the 9 vertical shafts were moved during this experiment. All horizontal shafts remained in open position (least blockage) to render a quasi-two-dimensional turbulence pattern with customized inflow angle variations. A velocity-specific transfer function was used to relate grid movement and resulting flow angle in order to implement the generation of sinusoidal inflow angle fluctuations in the flow.

3.4.2 Instrumentation

Model is instrumented with 48 pressure taps distributed in a span-wise staggered alignment to avoid wake interference. One tap is located at the leading edge, 25 taps along the upper surface, 21 taps along the lower surface and one tap is located at the trailing edge. The pressure taps with 0.3 mm diameter are connected to a system of three synchronized multi-channel scanners, which record the pressure at 100 Hz sampling frequency. The data acquisition with all sensors (pressure scanners, load cells, torque sensor, met sensors) are synchronized by means of a LabVIEW software and measurements are started upon a common trigger.

3.4.3 Measurement Campaign

The experiments were performed at two different Reynolds numbers of 0.5 and 0.9 million.

Airfoil model was tested at surface clean condition and also tripped at 1.5% of the chord in the suction side and 10% of the chord in the pressure side.

Laminar inflow conditions were obtained by mounting the closed test section of the wind tunnel directly to the outlet nozzle, in order to obtain classical airfoil polars as a baseline.

In this data set, two different customized turbulent flow cases are included: the open-grid case (all shafts of the grid remain in open position) and sinusoidal case (grid vertical axes have a sinusoidal motion of frequency 5Hz and amplitude 30º)

Aerodynamic coefficients data is obtained in two ways: integrating the model pressure taps distributions (these data is compiled in the so-called ‘pressure files’) and through the measurement of the force sensors (compiled in the ‘force files’).

4. Data published

The data have been published in the open access Zenodo repository under a Creative Commons Attribution-ShareAlike licence. Zenodo is a scientific open access repository launched by CERN within the EC funded research project OpenAIRE. The link to access the data is: https://doi.org/10.5281/zenodo.1135424

The data has been uploaded in asci format files together with:

- data in netCDF format
- script (jupyter notebook in python) for converting text format into netCDF
- script (jupyter notebook in python) for examples of data processing and visualization
- documentation
- Docker file defining the environment needed to open and process the files

Supported by:

4.1 ASCII data files description

In all the files the data is organized in 6 columns of data. The first row has the header with the name of each parameter.

Depending on each test and each type of data file, some parameters may not include data. In that case, the corresponding column is filled with character 'NaN'.

In general the data contained in each column are:

- Time: time in seconds of the measured values
- AoA: Angle of attack of the airfoil
- Flap: Flap angle deflection (only for CENER test)
- Cl: Aerodynamic lift coefficient
- Cdp: Aerodynamic pressure drag coefficient*
- Cm: Aerodynamic pitching moment coefficient
  (* *For some Oldenburg test files, this value correspond to total drag coefficient*. See below)

4.1.1 University of Glasgow tests data files

File names:

Data files name format begin with an eight digit number (abcdefgh_coeffs.dat), where: 'ab' is the model number (05 for NACA0015 and 09 for NACA0030); 'c' is the test type (in this data base all of them correspond to 0); 'd' is the motion type (0 – static , 1 – sinusoidal oscillation, 4 – unsteady static); 'efg' is the test number; 'h' is the attempt number at this test.

> Example: "05011141_coeffs.dat" (NACA0015, sinusoidal oscillation, test 114, attempt 1)

Each file contains the data organized in columns with this information:

- Time (in seconds): corresponding time of the measured values
- AoA (in degrees): Airfoil angle of attack
- Flap (in degrees): not applicable for these files. Contains 'NaN'
- Cl: Lift coefficient
- Cdp: Pressure drag coefficient
- Cm: Pitching moment coefficient

4.1.2 NREL experiments data files

File names:

The steady state and the dynamic polars have different file names formats.

The steady state polars have these fields:

- Name of the airfoil
- Character 'C' (standing for clean case)

- Reynolds number in tens of thousands
- Underscore followed by 'Coef'

  Example: "N4415C75_Coef.txt" (Static state polar of NACA4415 airfoil (clean case) at Reynolds Number of 0.75 million)

The dynamic polar names have these fields:

- Character 'C' (clean case)
- AoA amplitude: 5 = 5.5 deg, 10 = 10 deg
- Pitch oscillation frequency: l = 0.6 hz, m = 1.2 hz, h = 1.8 hz
- Reynolds number in tens of thousands
- Airfoil name (or abbreviation of it)

  Example: "C10m125_14_n4415.txt" (Clean case, 10 deg amplitude, 1.2 hz, Re=1.25 million, NACA4415 airfoil)

Each file contains the data organized in columns with this information:

- Time (in seconds): corresponding time of the measured values ('NaN' for static files)
- AoA (in degrees): Airfoil angle of attack
- Flap (in degrees): not applicable for these files. Contains 'NaN'
- Cl: Lift coefficient
- Cdp: Pressure drag coefficient
- Cm: Pitching moment coefficient

4.1.3 CENER experiments data files

File names:

All the data files begin with N64418 followed by an underscore and a capital letter (S, P, F or C). This letter indicates the type of test as described above:

- S: Baseline static polars
- P: AoA sinusoidal movements (pitch motion)
- F: Flap sinusoidal movement
- C: AoA & Flap combined sinusoidal movement

Depending on each type of test the file name has these other additional fields separated by underscores:

Case S: Only one field containing the Flap deflection:

Example: "N64418_S_F05" (polar with Flap 5o deflection)

Case P: Four fields following type of test:

N64418_P_Axx_xx_kx-xxx_Fxx

- Field 1: Axx: mean angle of attack value
- Field 2: xx: angle of attack amplitude
- Field 3: kx-xxx: reduced frequency
- Field 4: Flap position

Example: "N64418_P_A05_10_k0-100_F00" (Pitching motion with AoA mean value of 5º, amplitude of 10º and reduced frequency of 0.1. Flap at 0º.)

Case F: Four fields following type of test:

N64418_F_Axx_Fxx_xx_kx-xxx

- Field 1: Axx: AoA position
- Field 2: Fxx: mean flap value
- Field 3: xx: flap amplitude
- Field 4: kx-xxx: reduced frequency

Example: "N64418_F_A10_F00_05_k0-050" (Flap motion at AoA=10º with a Flap mean value of 0º and amplitude of 5º and a reduced frequency of 0.05.

Case C: Seven fields following type of test:

N64418_C_Axx_xx_kx-xxx_Fxx_xx_kx-xxx_Phxxx

- Field 1: Axx: mean AoA value
- Field 2: xx: AoA amplitude
- Field 3: kx-xxx: reduced frequency
- Field 4: Fxx: mean flap value
- Field 5: xx: flap amplitude
- Field 6: kx-xxx: flap reduced frequency
- Field 7: Phxxx: phase shift between both motions in degrees

Example: "N64418_C_A10_10_k0-050_F00_10_k0-050_Ph045" (Pitching motion with AoA mean value of 10º and amplitude of 10º combined with flap motion around 0º with amplitude of 10º. Both motions with reduced frequency of 0.05 and a phase shift of 45º)

Each file contains the data organized in columns with this information:

- Time (in seconds): corresponding time of the measured values ('NaN' for static 'S' files)
- AoA (in degrees): Airfoil angle of attack
- Flap (in degrees): Flap angle deflection
- Cl: Lift coefficient
- Cdp: Pressure drag coefficient
- Cm: Pitching moment coefficient

4.1.4 University of Oldenburg test data files

File names:

The file names are composed of 4 fields separated by underscores and end with a score followed by 'Pressure' or 'Balance' indicating if they are Pressure files or Force files respectively. The 4 fields show this information:

Field 1: number of original polar

Field 2: type of flow

laminar: no grid installed

opngrid: grid in open static position

sinusoi: grid with vertical axis moving in sinusoidal mode

Field 3: 'cl' for clean surface polars. 'tr' for tripped polars

Field 4: Reynolds number ('500k' for 0.5 million and '900k' for 0.9 million)

Example: "188_sinusoi_tr_900k-Pressure.txt" (Polar nº 188 with sinusoidal grit movement, Reynolds number 0.9 million and with pressure data)

Each file contains the data organized in columns with this information:

- Time (in seconds): not applicable for these files. Contains 'NaN'
- AoA (in degrees): Airfoil angle of attack
- Flap (in degrees): not applicable for these files. Contains 'NaN'
- Cl: Lift coefficient
- Cdp:
  - For 'pressure files': Pressure drag coefficient
  - For 'force files': Drag coefficient (Cd)
- Cm: Pitching moment coefficient

4.2 Data at Windbench

Apart from the Zenodo publication, model benchmarking exercises are available in windbench.net platform. Windbench.net is an online repository of numerical models, model benchmarking exercises and related projects. Windbench implements the model evaluation protocol that has been developed during the IEA- Task 31 WAKEBENCH and IRPWind projects [6]

Windbench also provides a free "sandbox" service where the published data and scripts can be accessed, edited and tried out in a fully functional environment. Some screenshots from this functionality are shown in Figure 8.

Supported by:

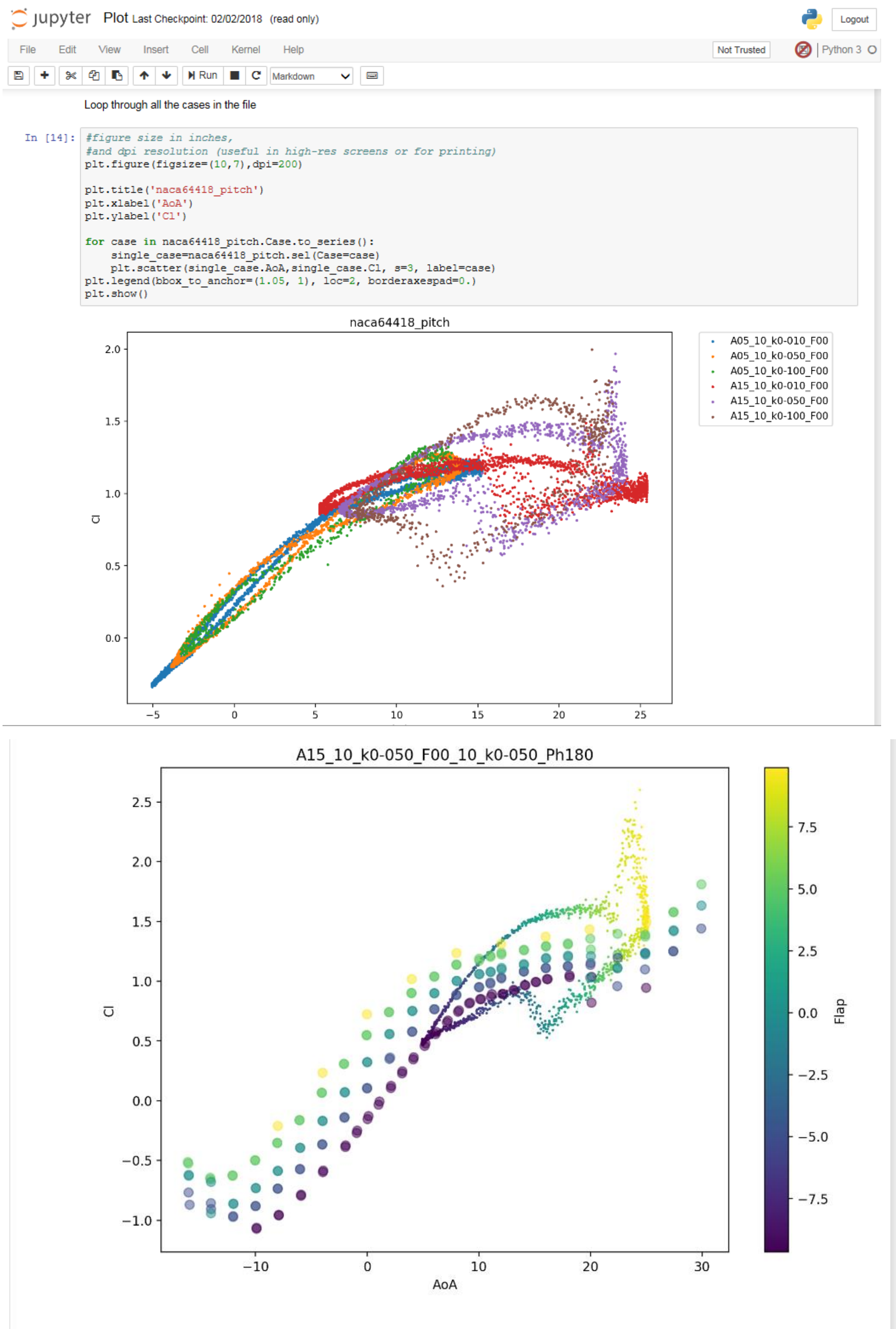

Figure 8. Screenshots from Windbench Sandbox utility

5. Conclusions

A specific database for the wind turbine airfoil unsteady aerodynamic analysis has been extracted from some of the most extensive and reliable experiments performed.

The data has been published in open access with the need information and tools for further investigations in this area.

6. References

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