README: Low-Reynolds-Number Pitching Airfoil Direct Numerical Simulations

Scott T. M. Dawson *

Overview

This README described the pitching airfoil direct numerical simulation dataset that is part of "A database for reduced-complexity modeling of fluid flows" [2]. Users of these data should cite the following references:

A. Towne, S. Dawson, G. A. Brès, , A. Lozano-Durán, T. Saxton-Fox, A. Parthasarthy, A. R. Jones, H. Biler, C.-A. Yeh, H. Patel, and K. Taira. A database for reduced-complexity modeling of fluid flows. *AIAA Journal*, 61:2867–2892, 2023

Scott T. M. Dawson, Daniel C. Floryan, Clarence W. Rowley, and Maziar S. Hemati. Lift enhancement of high angle of attack airfoils using periodic pitching. *AIAA Paper 2016-2069*, 2016

Flow conditions

This dataset considers a two-dimensional flat plate airfoil at low Reynolds number and high angle of attack, which is pitching sinusoidally about its midchord with an amplitude of 5°. The relevant dimensionless parameters are:

- Reynolds number: $Re = \frac{U_\infty c}{\nu} = 100$
- Dimensionless pitching frequency $f_P = \frac{fc}{U_\infty} \in \{0.05, 0.1, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5\}$
- Pitching amplitude $\alpha_P = 5°$
- Base angle of attack $\alpha_0 \in \{25°, 30°\}$

Here, u_∞ is the freestream velocity, c is the airfoil chord length, and ν is the kinematic viscosity. With the parameters described above, the airfoil pitches with kinematics described by

$$\alpha(t) = \alpha_0 - \alpha_P \sin(2\pi f_P t),$$

Data collection

Direct numerical simulations of the incompressible Navier–Stokes equations are performed using an immersed boundary projection method. With this method, the fluid computations are solved on a set of four nested uniform spatial grids, with the finest grid having a spacing of $0.02c$ in both the $x-$ and $y-$directions. Each grid consists of 600×300 grid points, with the spatial extent doubling (and thus the resolution halving) from one grid to the next. The total computational domain extends 96 and 48 chord lengths in the streamwise and transverse directions, respectively. The boundary conditions of the airfoil are imposed by applying body

*Illinois Institute of Technology, Chicago, IL 60616

forces at locations along the surface of the moving airfoil. These body forces are spaced 0.02c apart. The midchord of the airfoil is located at $(x, y) = (0.5, 0)$.

Simulations are run for 50 convective time units before data is collected. For each simulation, the dataset includes time-resolved velocity (streamwise and transverse components) and vorticity fields with a timestep of $0.1c/U_\infty$, on the finest computational grid, which is 12 and 6 chord lengths in the streamwise and transverse directions, respectively. The dataset includes 401 velocity and vorticity snapshots (corresponding to 40 convective time units) for the $\alpha_0 = 25°$ cases, and 1001 snapshots (100 convective time units) for the pitching $\alpha_0 = 30°$ cases. The dataset also includes the airfoil lift (C_l) and drag (C_d) coefficients, the angle of attack (α) and angular velocity ($\dot{\alpha}$), and the coordinates of the airfoil itself, all collected with a timestep of $0.01U_\infty/c$.

As well as data for the pitching airfoil, stationary airfoil data is included for both $\alpha_0 = 25°$ and $30°$. In the $\alpha_0 = 25°$ case, the equilibrium is stable, so only a single snapshot of data (and single value of C_l and C_d) is included. For $\alpha_0 = 30°$, the wake is unstable, and so time-varying quantities are collected using the same parameters as for the pitching cases (with 401 velocity and vorticity snapshots collected over 40 convective time units). All data is stored in double-precision format.

Nondimensionalization

The data are nondimensionalized using the following quantities

$$\boldsymbol{u} = \frac{\boldsymbol{u}^*}{U_\infty^*}, \qquad \boldsymbol{x} = \frac{\boldsymbol{x}^*}{c^*}, \qquad t = \frac{t^* U_\infty^*}{c^*}, \qquad C_l = \frac{F_y^*}{0.5\rho^* c^* U_\infty^*} \qquad C_d = \frac{F_x^*}{0.5\rho^* c^* U_\infty^*}$$

Here, the superscript $*$ refers to the dimensional quantity. F_x^* and F_y^* denote the dimensional forces parallel and perpendicular to the freestream, with the corresponding dimensionless quantities C_l and C_d being the lift and drag coefficients.

File inventory

The database contains the following files and variables:

- `airfoilDNS_example.zip`: zip archive containing a representative subset of the following data and scripts as an entry point for users
- `airfoilDNS_read.m`: Matlab script showing how the data can be read and manipulated
- `airfoilDNS_parameters.h5`: hdf5 file containing flow and data parameters
  - `Re`: Reynolds number
  - `alpha_0s`: Base angles of attack included in dataset
  - `alpha_p`: Pitching amplitude
  - `f_p`: Pitching frequencies included in dataset
  - `pitch_axis`: Pitch axis location on airfoil, (where 0 corresponds to leading edge, 1 to trailing edge)
  - `dt_fields`: timestep between successive field variable snapshots
  - `dt_forces`: timestep between successive force (and other scalar quantity) variable snapshots
- `airfoilDNS_grid.h5`: hdf5 file containing grid information
  - `x`: streamwise grid
  - `y`: wall-normal grid
- `airfoilDNS_a##f##.h5`: hdf5 file containing data for pitching at specified base angle of attack and frequency

- ux: instantaneous streamwise velocity field at each (x, y) grid point and at each time t_field
- uy: wall-normal velocity at each (x, y) grid point and at each time t _field
- vort: vorticity at each (x, y) grid point and at each time t_field ffa
- t_field: times where field variables are collected (relative to start of simulation)
- t_force: times where force (and other scalar) variables are collected (relative to start of simulation)
- alpha: airfoil angle of attack at each time t_force
- alphadot: airfoil rotation rate at each time t_force
- Cl: airfoil lift coefficient at each time t_force
- Cd: airfoil drag coefficient at each time t_force
- xa: x-component of airfoil coordinates at each time t_force
- ya: y-component of airfoil coordinates at each time t_force

■ airfoilDNS_a25static.h5: hdf5 file containing data for stationary airfoil at $\alpha = 25°$

- ux: equilibrium streamwise velocity field at each (x, y) grid point
- uy: equilibrium wall-normal velocity at each (x, y) grid point
- vort: equilibrium vorticity at each (x, y) grid point
- alpha: airfoil angle of attack (value of 25)
- alphadot: airfoil rotation rate (value of 0)
- Cl: equillibrium airfoil lift coefficient
- Cd: equillibrium airfoil drag coefficient
- xa: x-component of airfoil coordinates
- ya: y-component of airfoil coordinates

■ airfoilDNS_a30static.h5: hdf5 file containing data for stationary airfoil at $\alpha = 30°$

- ux: instantaneous streamwise velocity field at each (x, y) grid point and at each time t_field
- uy: wall-normal velocity at each (x, y) grid point and at each time t _field
- vort: vorticity at each (x, y) grid point and at each time t_field
- t_field: times where field variables are collected (relative to start of simulation)
- t_force: times where force (and other scalar) variables are collected (relative to start of simulation)
- alpha: airfoil angle of attack (value of 30)
- alphadot: airfoil rotation rate (value of 0)
- Cl: airfoil lift coefficient at each time t_force
- Cd: airfoil drag coefficient at each time t_force
- xa: x-component of airfoil coordinates
- ya: y-component of airfoil coordinates

■ calc_dmd.m: Matlab function containing a simple implementation of dynamic mode decomposition

References

[1] Scott T. M. Dawson, Daniel C. Floryan, Clarence W. Rowley, and Maziar S. Hemati. Lift enhancement of high angle of attack airfoils using periodic pitching. *AIAA Paper 2016-2069*, 2016.

[2] A. Towne, S. Dawson, G. A. Brès, , A. Lozano-Durán, T. Saxton-Fox, A. Parthasarthy, A. R. Jones, H. Biler, C.-A. Yeh, H. Patel, and K. Taira. A database for reduced-complexity modeling of fluid flows. *AIAA Journal*, 61:2867–2892, 2023.