Introduction

Recent interest in air vehicle gust-response, wind-energy and high-speed rotorcraft, among other applications, has focused attention on surging (streamwise oscillation of) airfoils. Airfoils may be subject to simultaneous surge and pitch, where the flow can be attached, partially separated, or massively separated. Under these unsteady conditions, there is often a desire to control these flows with the objective, for example, of minimizing unsteady loads or maximizing net aerodynamic efficiency.

This resource contains, inter alia, surge and pitch data acquired on a NACA 0018 airfoil in a specially designed unsteady wind tunnel. Data includes active flow control, introduced by means of a blowing slot, near the airfoil leading-edge. The data sets consist of surface pressure measurements, integrated aerodynamic coefficients, and selected two-dimensional particle image velocimetry (PIV). The intention is to provide data sets for validation of CFD codes, development of low-order models, and to provide comparisons with other unsteady facilities.

Data Format

- The experimental data is grouped into data sets. All data sets are listed in the overview on page 5.
- Each data set comprises several measurements, each of which is identified by a four-digit number.
- The data file “*FCL_pressure_data.zip*” contains the phase averaged data for all data sets shown here.
- For each measurement, data is provided in three different formats:
  - EXCEL (.xlsx)
  - Matlab (.mat)
  - Tab-delimited spreadsheet (.txt)

  While all files contain the same basic data, the Excel and Matlab files also include the (phase-) averaged pressure distributions.
- A nomenclature is provided at the end of this document.
- The pressure distributions are provided in the form of matrices, where the first index corresponds to the angle of attack (quasi-steady pitch) or the phase angle (unsteady data) respectively and the second index corresponds to the pressure port.
- Two-dimentional PIV data is available for data sets 99930, 99932 and 99936. The data files “FCL_PIV_data_999**.zip“ contain the phase averaged velocity fields in a tab-delimited format as well as plots of the flow fields, vorticity distributions and simultaneously recorded phase averaged surface pressure distributions. For more detail, see

Müller-Vahl, H., Strangfeld, C., Nayeri, C.N., Paschereit, C.O. and Greenblatt, D., “Control of Thick Airfoil Deep Dynamic Stall Using Steady Blowing,” AIAA Journal, Vol. 53, No. 2, 2015, pp. 277-295.

The Unsteady Wind Tunnel

Figure 1. Photograph of the louver system attached to downstream test section for the present experiments with the radial diffuser removed (vanes fully open).

The Technion's Unsteady Low-Speed Wind Tunnel (UWT) is a blowdown facility powered by a 75kW double-entry (laterally-symmetric), backward-bladed centrifugal "airfoil-type" blower. The impeller lateral symmetry minimizes side-to-side vibrations and backward-blading produces a smooth pressure rise in the blade-stall regime. The blower is coupled to a large angle (20.6° half-angle divergence) diffuser and a coarse mesh was installed at the midpoint of the diffuser. A flexible rubber blower-diffuser coupling isolates blower vibrations. The diffuser connects to an anti-swirl section and a segmented plenum, where a coarse mesh is mounted between the first and second plenum segments. An 8:1 composite contraction nozzle, constructed from four identical sides, produces a 1000x610mm exit nozzle that discharges into the 1004x610x2000mm test sections.

A louver system, adopted to force unsteady oscillation, is mounted on the furthest downstream test section module. Finally, the air discharges into a radial diffuser. Under steady conditions, with the louvers removed, the maximum wind speed is 55m/s and flow distortion and overall turbulence level, in the upstream test section module, are less than 0.2% and 0.1% respectively. The louver mechanism comprises N=13 counter-rotating vanes, each vane has a chord length of l_v=70 mm, thickness of t_v=4 mm and spans the entire width (w) of the test section module exit (see Figure 1). A 750 watt computer-controlled servo-motor with a 5:1 gear ratio was attached to the central vane, thus enabling the dynamic control of the vanes' position, and the programming of arbitrary rotation profiles.

The Pitching Mechanism

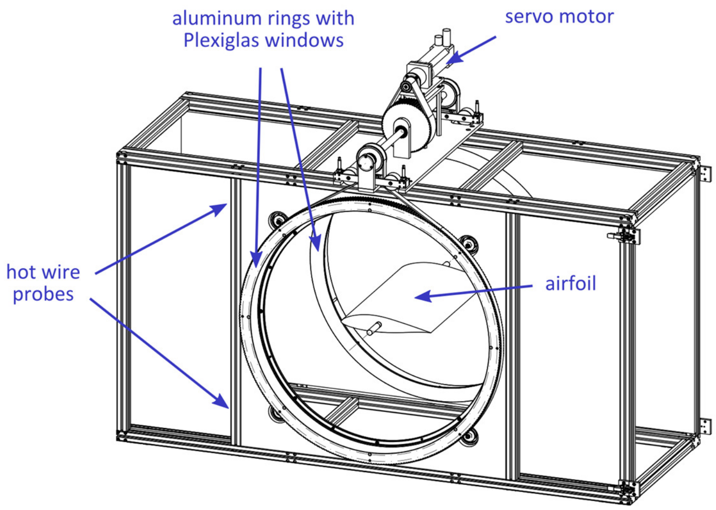


Figure 2. Schematic of the test showing the servo-motor and belt drives as well as the airfoil location.

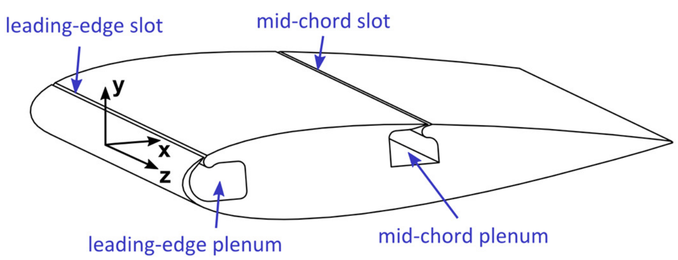


Figure 3. Schematic of the NACA 0018 airfoil showing leading-edge and mid-span blowing slots.

The test section is equipped with large rings, each mounted on four bearings, and transparent Plexiglas windows (Figure 2). The rings are driven by a servo-motor via two belt drives. The floor and ceiling are also constructed from Plexiglas, rendering full optical access to the test section. The rings can perform arbitrary pitching motion of the airfoil through a full 360° at a maximum rate of 150°/s. This custom built test section with arbitrarily large angle-of-attack range, combined with high pitching speeds and full optical access renders this setup unique. This system, in conjection with the louver system, was programmed using LabVIEW with the so-called CompactRIO (or cRIO) real-time controller (National Instruments).

Data were acquired on a NACA 0018 airfoil (chord length c=0.348m, span s=0.610m) by mounting it between the Plexiglas windows with the axis of rotation located at 25% chord. A schematic of the airfoil is shown in Figure 3. The airfoil was equipped with 40 mid-span surface pressure ports (ID 0.8mm) symmetrically distributed along the upper and lower surfaces. Six additional pressure ports were located at chordwise positions of x/c = 21.5% and x/c = 69.5% on the suction surface as well as x/c = 69.5% on the pressure surface at a distance of 100mm from each side wall (z/s ≈ 0.16 and 0.84 respectively). The airfoil was mounted inverted in the test section (slots below) to facilitate PIV measurements. The mid-chord control slot was sealed with thin (75μm) adhesive tape to minimize the impact of the surface discontinuity. The leading-edge control slot, located at 5% chord, was left open during all measurements presented here to facilitate a direct comparison between baseline and control test cases.

Slot Blowing Systems

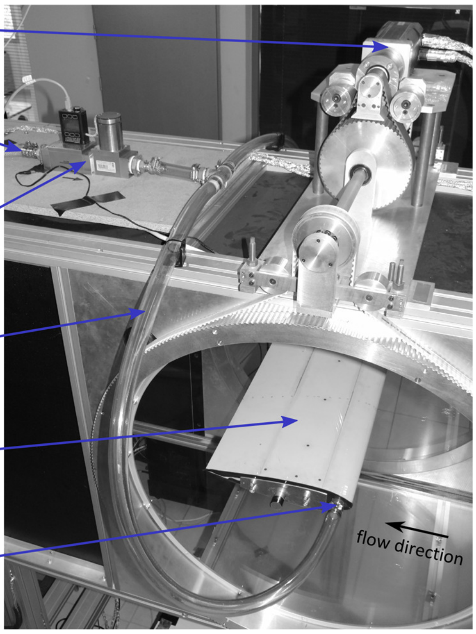


Figure 4. Photograph of the slot blowing system.

Preliminary blowing data (indicated below by *) was recorded using an SMC Pneumatics AW40-F04 pressure regulator and monitored with a Dwyer Instruments "VFC-122-EC" rotameter (accuracy 4.7·10−4m3/s). Pressurized air from the rotameter entered the airfoil plenum from both sides symmetrically to minimize spanwise deviations of slot velocity. For unsteady and adaptive blowing data sets, the pressure regulator was replaced with an Alicat Scientific "MCR 3500" mass flow controller. According to manufacturer specifications, the mass flow controller accuracy is ±(0.8% of reading + 0.2% of full scale). A Ceccato "CDX 36" refrigeration dryer was installed upstream of the controller. The mass-flow controller and associated tubing are shown in Figure 4.

Data Acquisition Procedure

The data acquisition was synchronized and automated using LabView with a trigger signal generated by the angle of attack motor controller serving as the reference. The surface pressure distributions and the wind tunnel speed were continuously recorded at a sample rate of 499 Hz and subsequently phase averaged. In all experiments, the wind tunnel speed was monitored with two hot wire probes located upstream of the airfoil model with the instantaneous value of U_∞ taken as the mean value of the two measurements. For the quasi-steady tests, the airfoil was pitched at a rate of 0.36°/s. Data obtained during three runs was ensemble averaged over windows with a width of $\Delta\alpha = 1°$ to reduce statistical uncertainty. During the unsteady experiments, data was continuously acquired for 100s and the first two pitching cycles were discarded. This procedure was repeated 4 times, providing data for a total of at least 300 cycles for each test case. The unsteady data was phase averaged over windows with a width of $\Delta\phi = 2°$. The aerodynamic coefficients were then calculated from the integral values of the phase averaged surface pressure distributions. The drag coefficient is based on pressure drag alone. The 95% confidence intervals of the lift coefficient and the moment coefficient were below $\Delta c_l = \pm 0.02$ and $\Delta c_m = \pm 0.01$ respectively. For more detail, see

Müller-Vahl, H., Nayeri, C.N., Paschereit, C.O. and Greenblatt, D., "Dynamic stall control via adaptive blowing," Renewable Energy, Vol. 97, 2016, pp. 47-64.

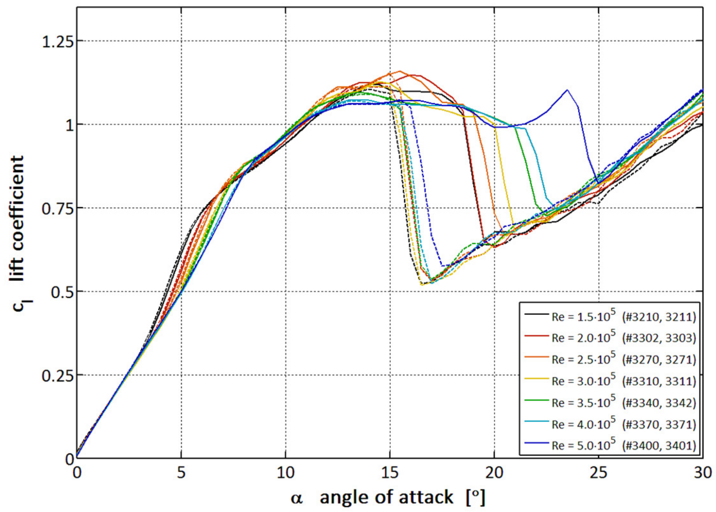
control	data set	inflow	Re	AoA	k
baseline	99900	quasi-steady pitch	various Re	-2° ≤ α ≤ 32°	0
	99930 + PIV data	dynamic pitch	various Re	10°+10°sin(φ)	various k
	99932 + PIV data	dynamic pitch & surge	250k* [1+0.5sin(φ-τ)]	10°+10°sin(φ)	0.074
steady blowing	99901	quasi-steady pitch	300k	-2° ≤ α ≤ 32°	0
	99910	surge	300k* [1+0.2sin(φ)]	15°	0.05
	99920	dynamic pitch	300k	18°+7°sin(φ)	0.06
	99922 99924	dynamic pitch	300k	18°+7°sin(φ)	0.09
	99926	dynamic pitch	300k	14.5°+3°sin(φ)	0.041
	99928	dynamic pitch	300k	14.5°+3°sin(φ)	0.082
	99936* + PIV data	dynamic pitch	250k	15°+10°sin(φ)	0.074
adaptive blowing	99940	surge	300k* [1+0.2sin(φ)]	15°	0.05
	99950	dynamic pitch	300k	18°+7°sin(φ)	0.01, 0.06, 0.09
	99952	dynamic pitch	300k	18°+7°sin(φ)	0.06
	99964	dynamic pitch & surge	300k* [1+0.2sin(φ)]	18°+7°sin(φ)	0.06
	99966	dynamic pitch & surge	300k* [1+0.2sin(φ-180°)]	18°+7°sin(φ)	0.06

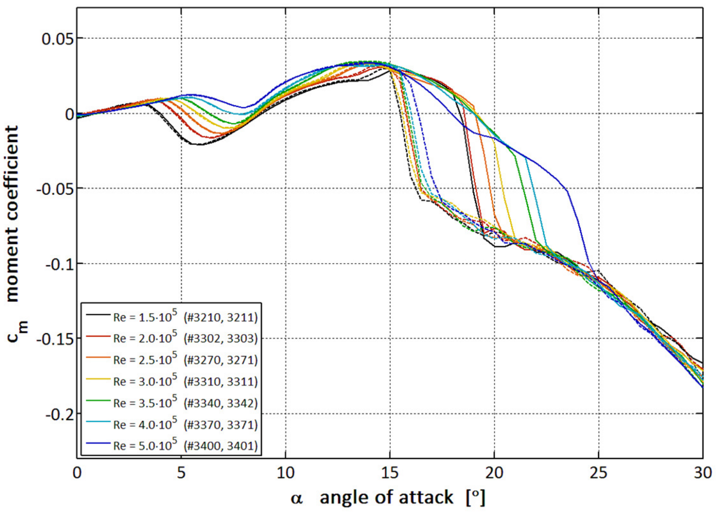
* Data set 99936 was recorded with the preliminary blowing setup, using a Dwyer Instruments "VFC-122-EC" rotameter to monitor the blowing mass flow rate.

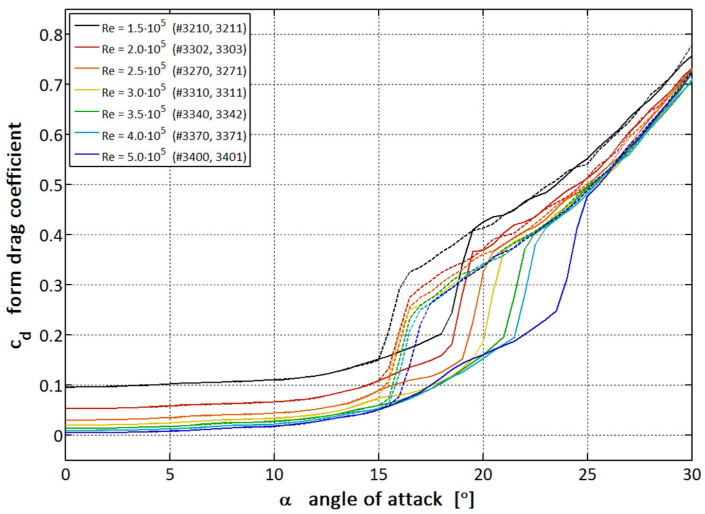
data set 99900

control: baseline **Re:** multiple Re **k:** 0

inflow: quasi-steady pitch **AoA:** -2° ≤ α ≤ 32°

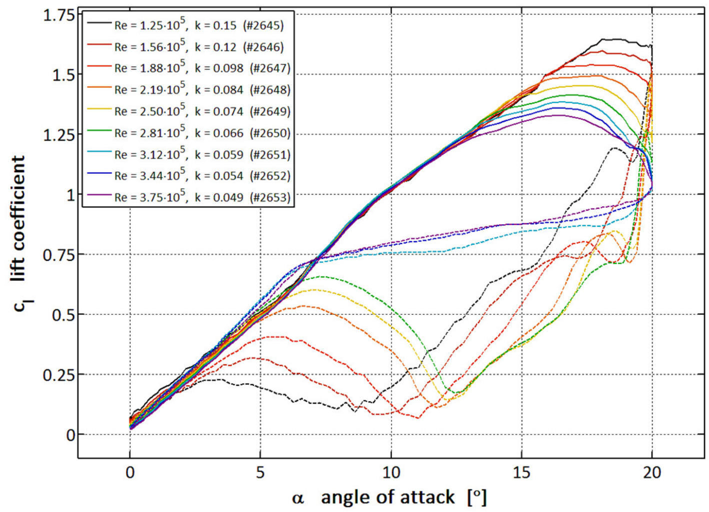


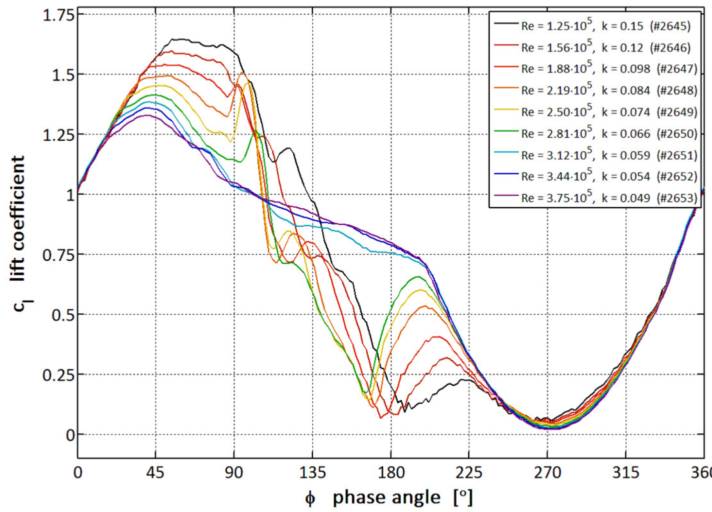


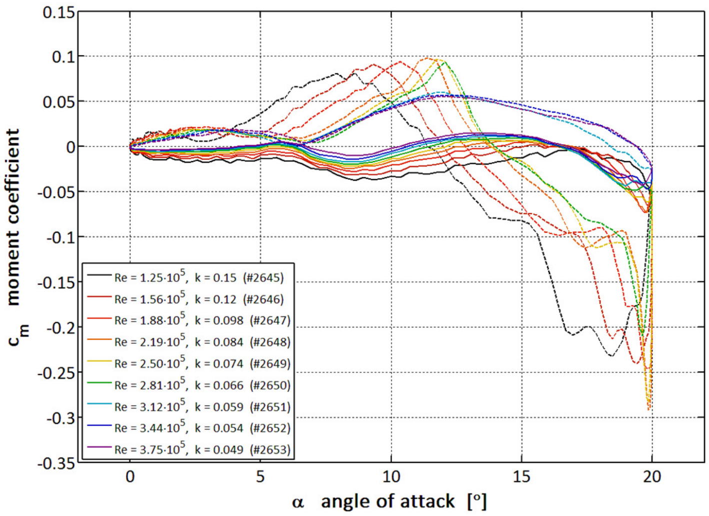


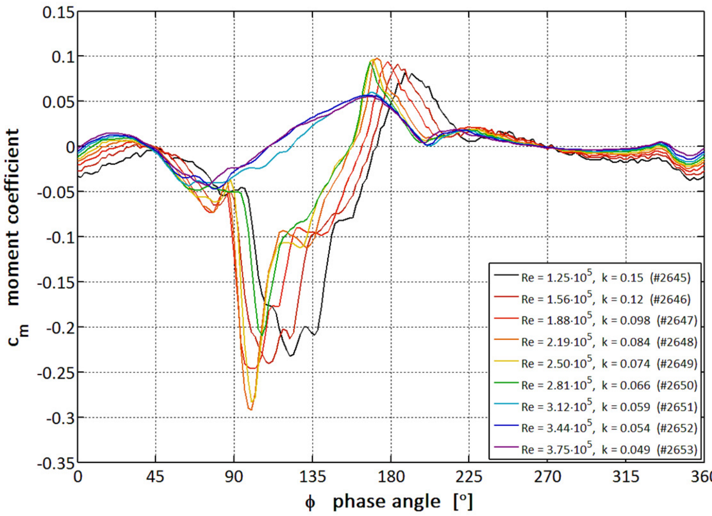
control: baseline **Re:** various Re **k:** various k

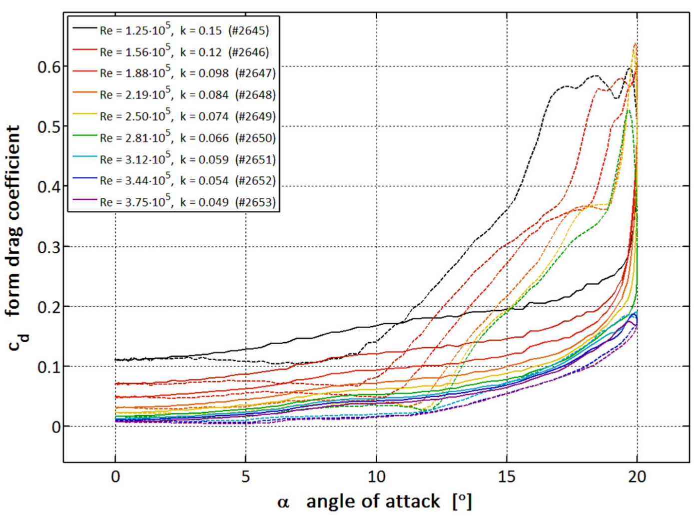
inflow: pitch **AoA:** 10°+10°sin(φ)

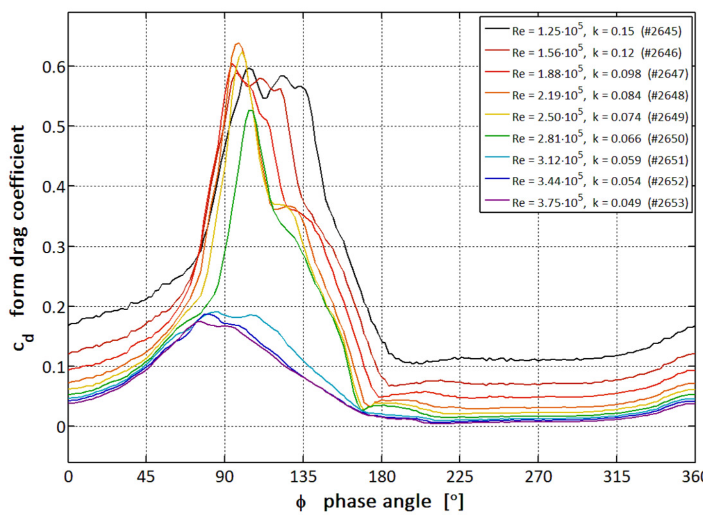








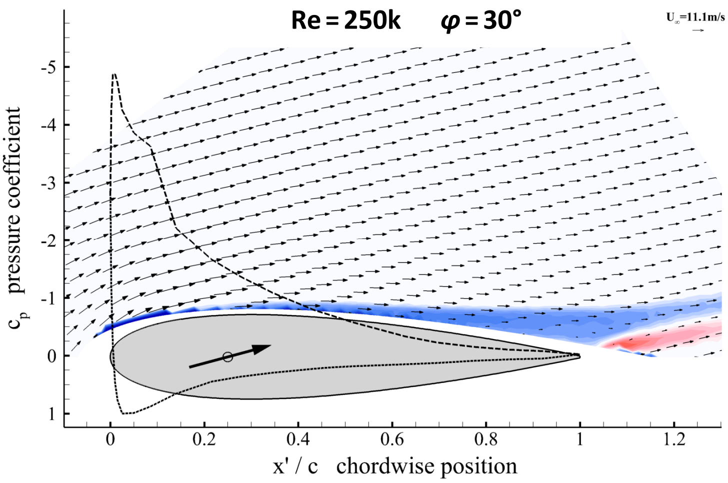


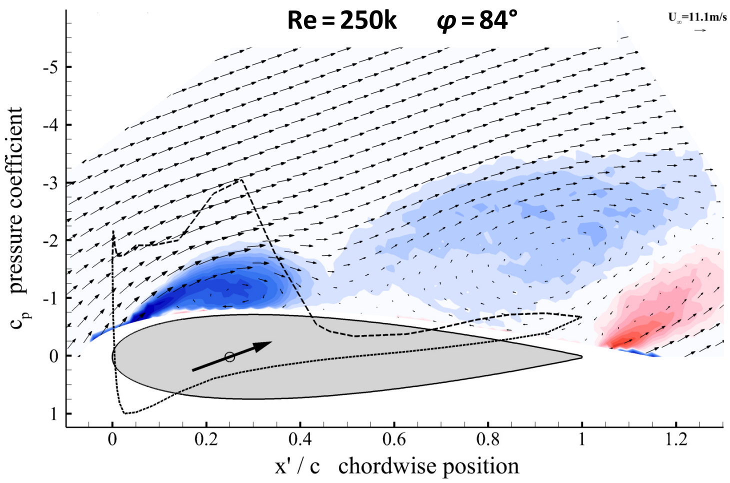


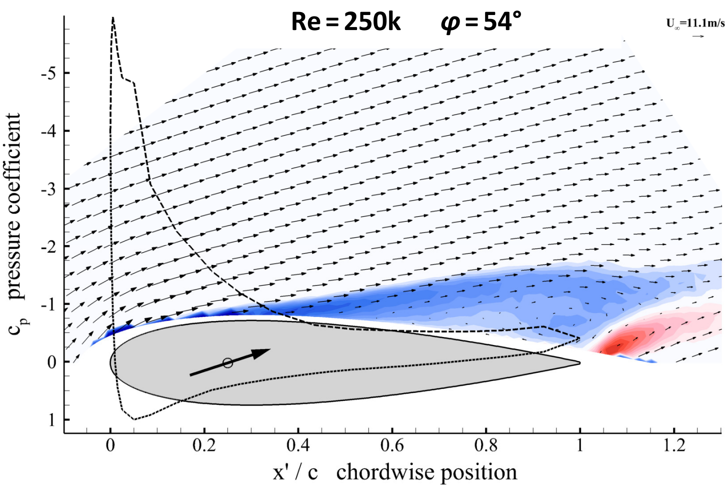
control: baseline **Re:** various Re **k:** various k

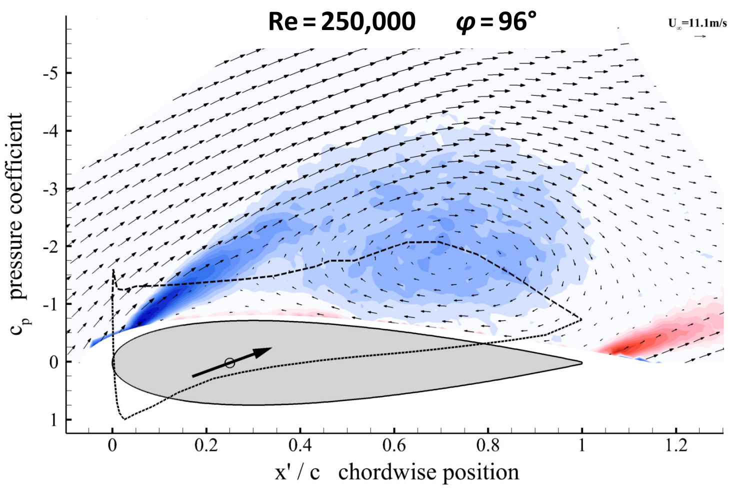
inflow: pitch **AoA:** 10°+10°sin(φ)

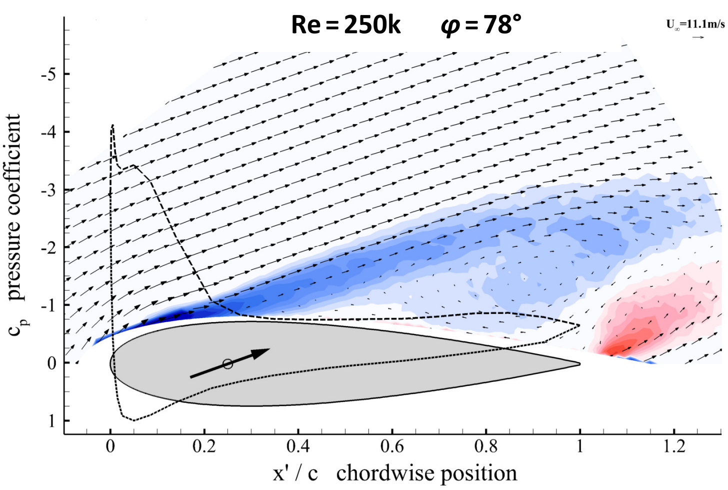
PIV data:
"FCL_PIV_data_99930.zip"

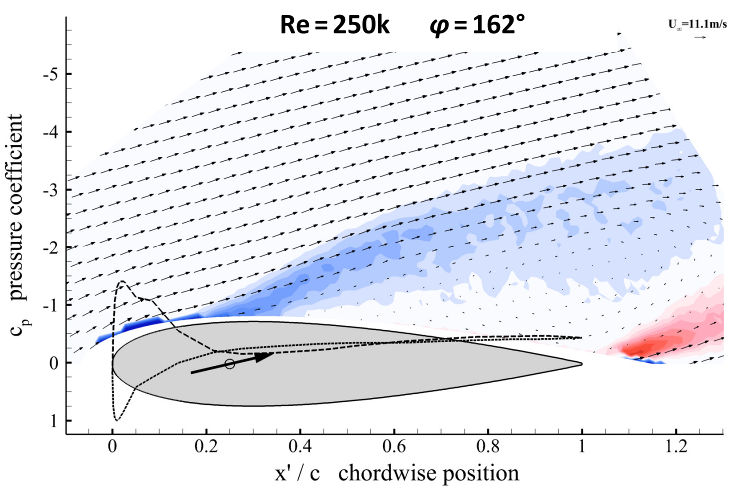








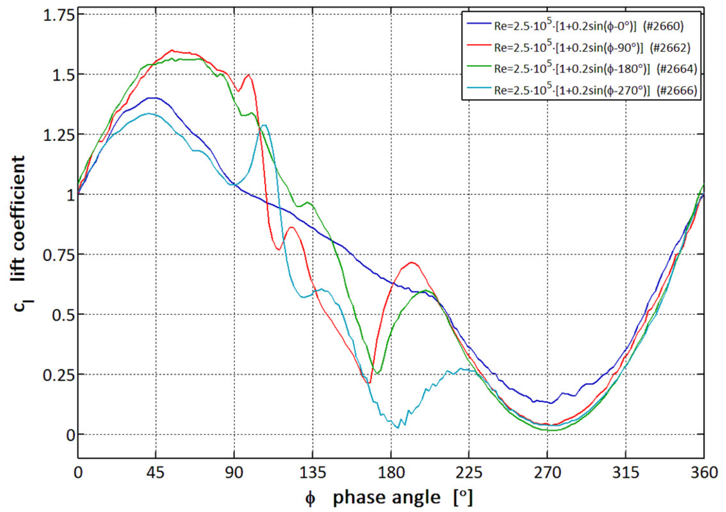


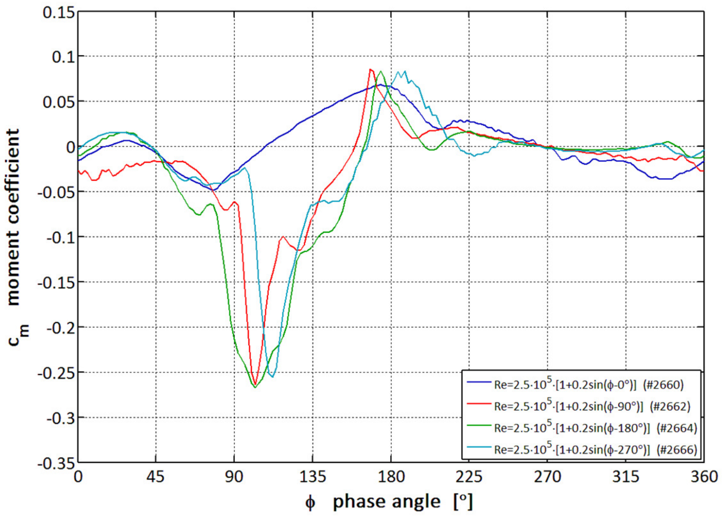


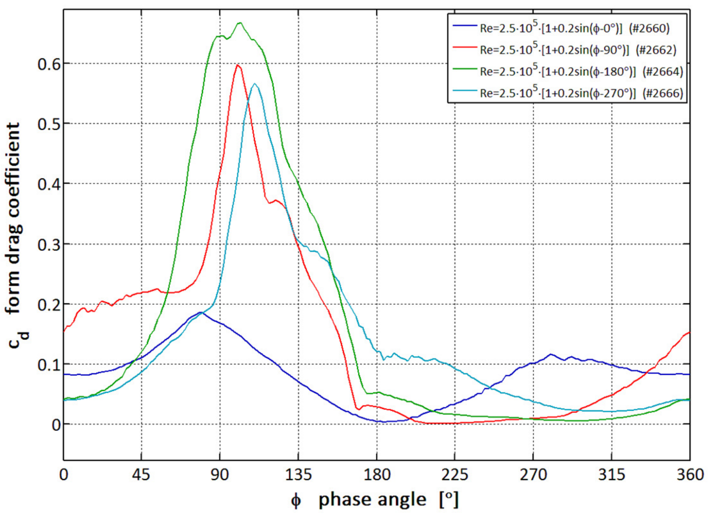
data set 99932

control: baseline **Re:** 250k* [1+0.5sin(φ-τ)] **k:** 0.074

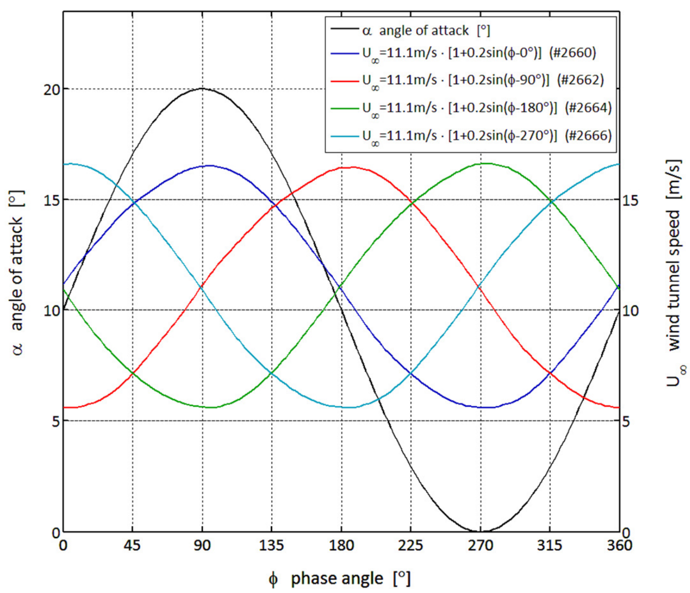
inflow: dynamic pitch & surge **AoA:** 10°+10°sin(φ)







phase averaged inflow

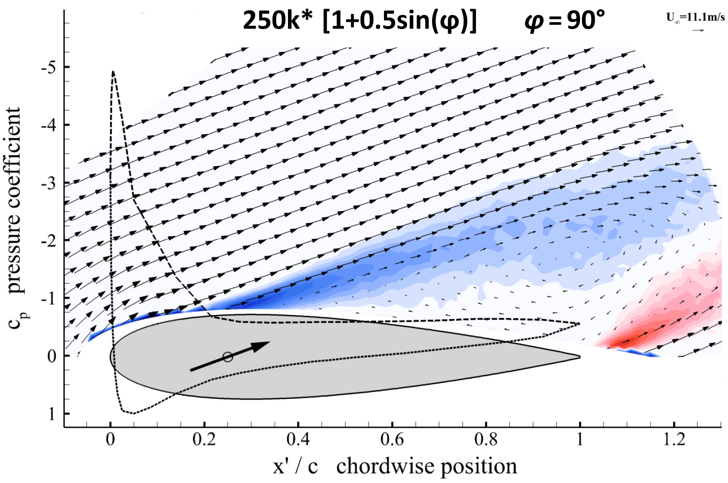


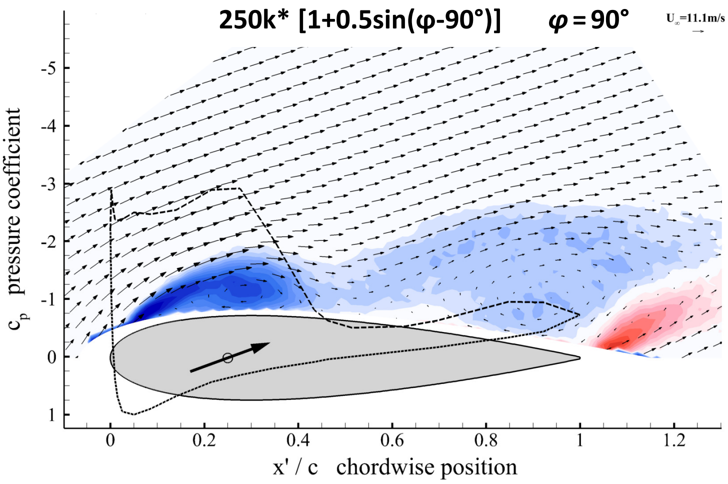
data set 99932

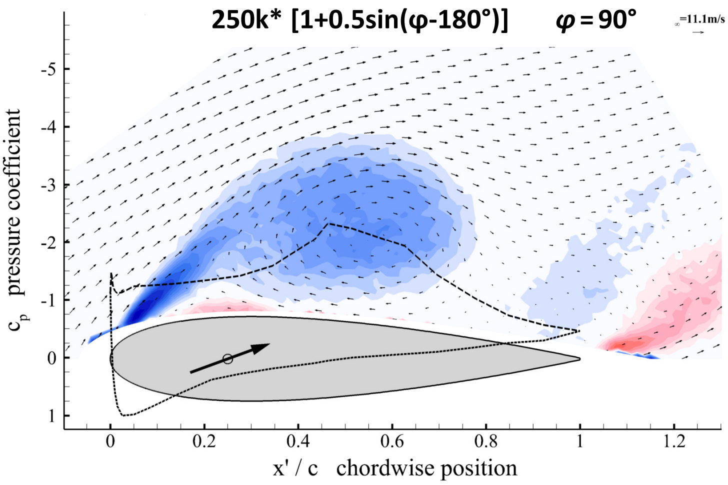
control: baseline **Re:** 250k* [1+0.5sin(φ-τ)] **k:** 0.074

inflow: dynamic pitch & surge **AoA:** 10°+10°sin(φ)

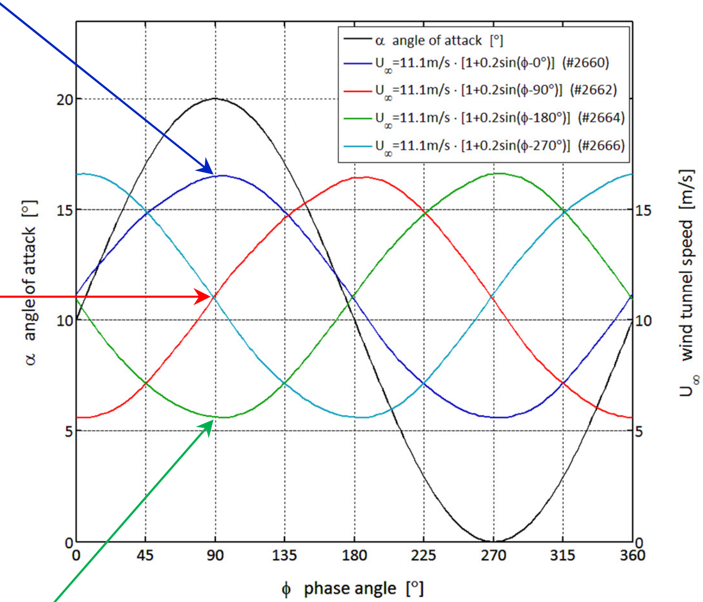
PIV data:
“FCL_PIV_data_99932.zip“







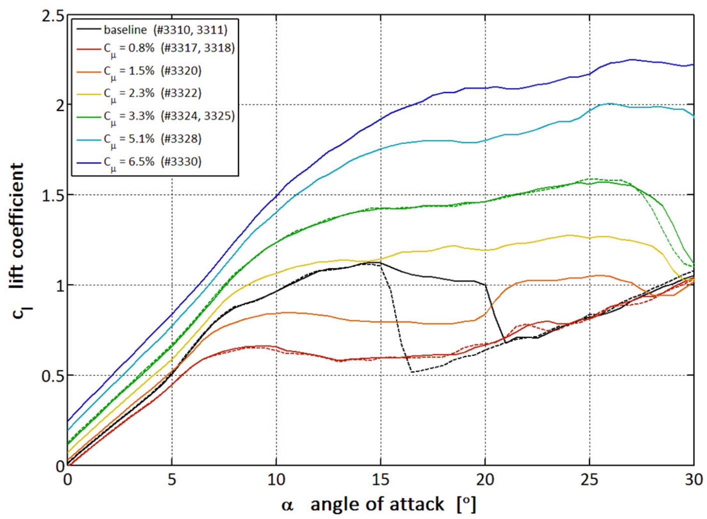
phase averaged inflow

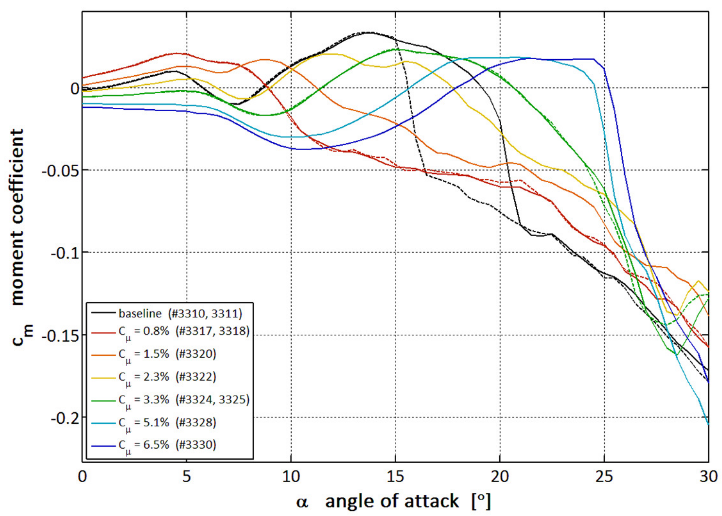


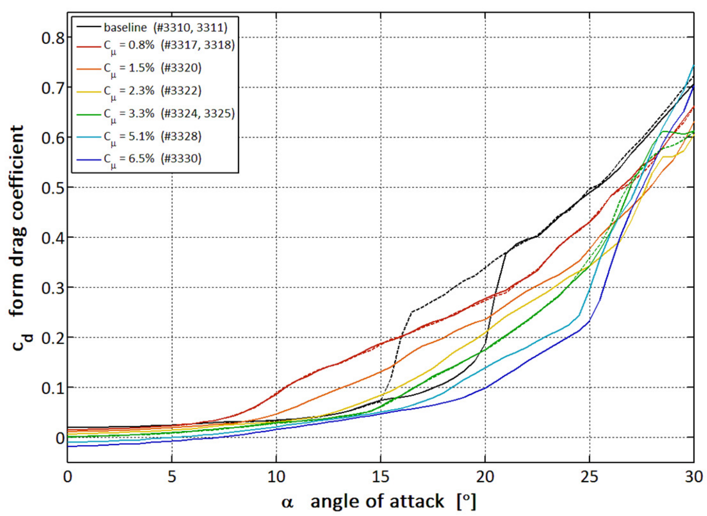
data set 99901

control: steady blowing **Re:** 300k **k:** 0

inflow: quasi-steady pitch **AoA:** -2° ≤ α ≤ 32°



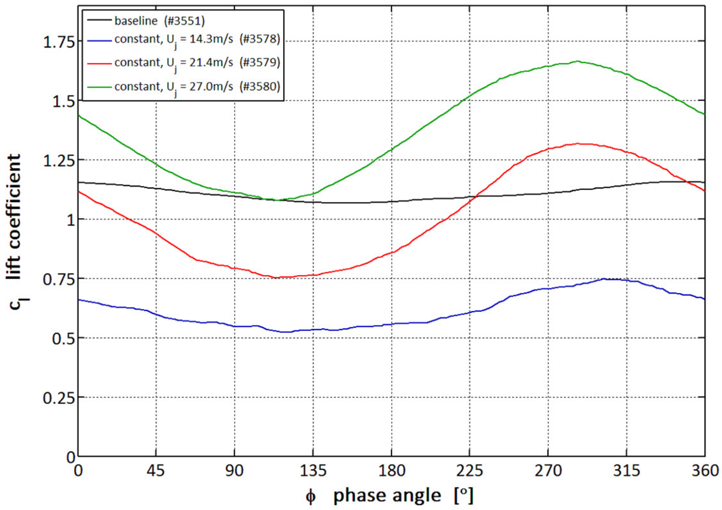


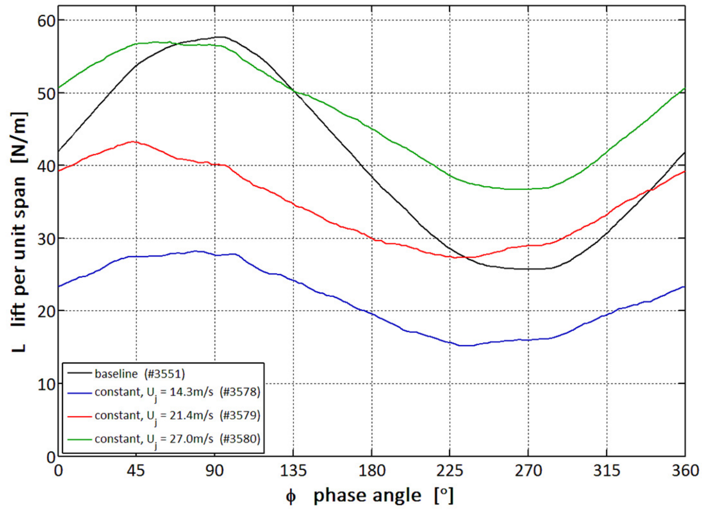


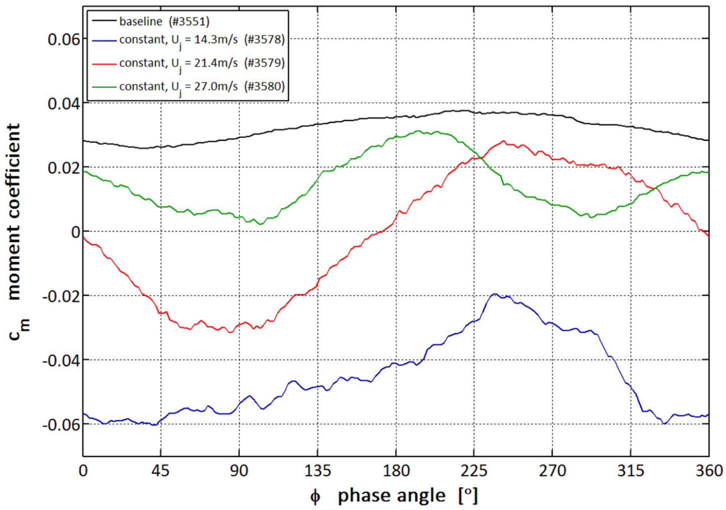
data set 99910

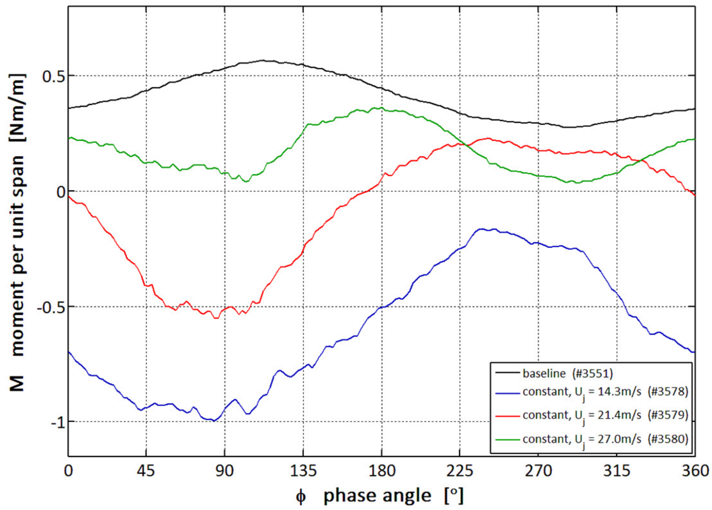
control: steady blowing **Re:** 300k* [1+0.2sin(φ)] **k:** 0.05

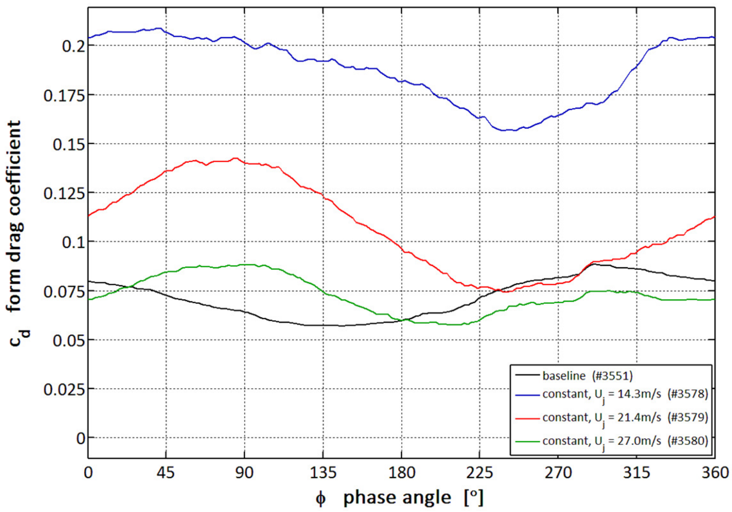
inflow: surge **AoA:** 15°







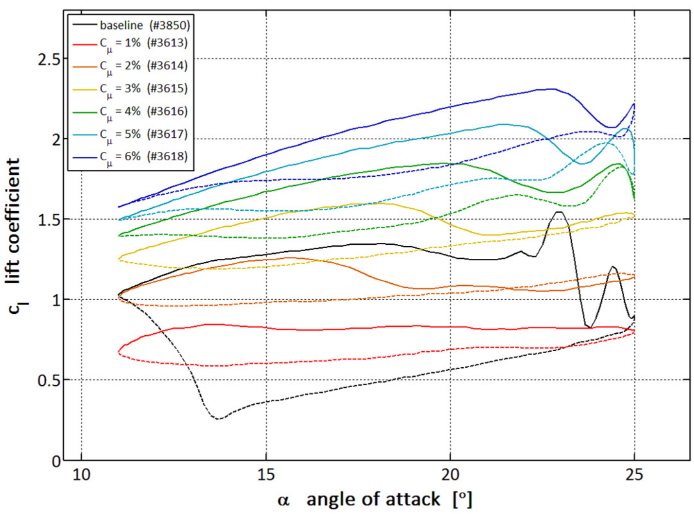


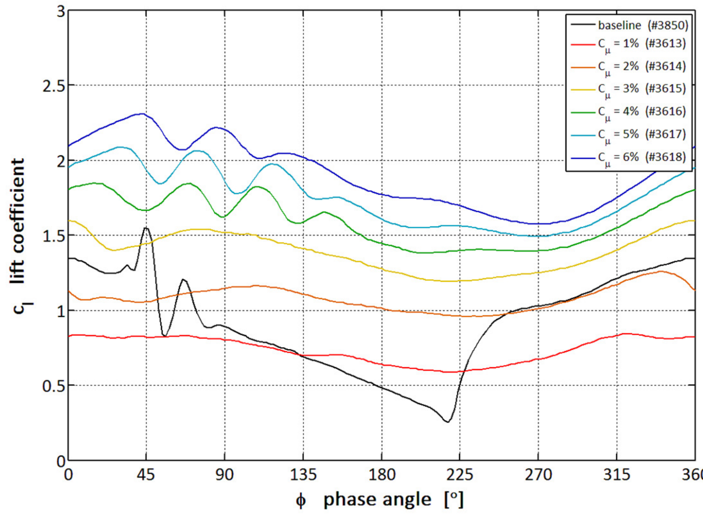


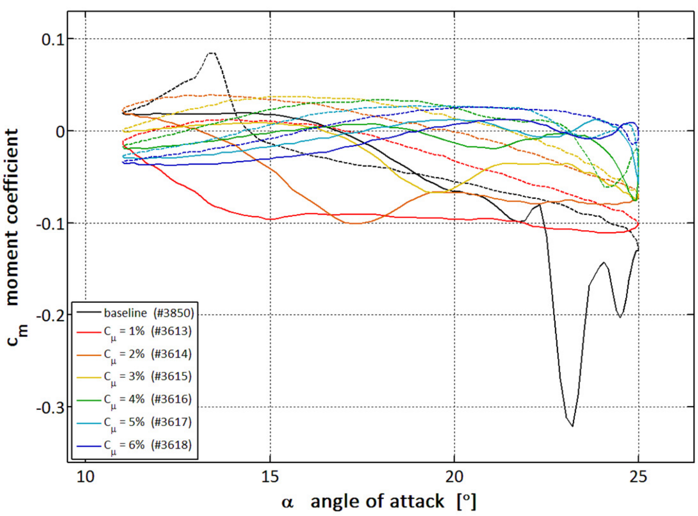
data set 99920

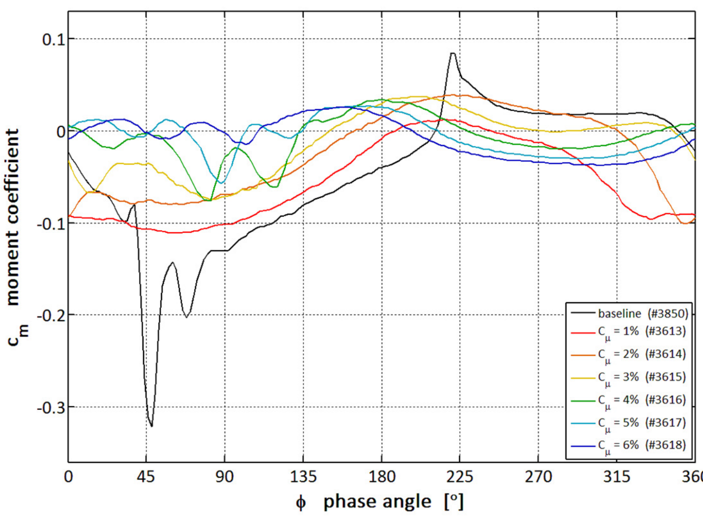
control: steady blowing **Re:** 300k **k:** 0.06

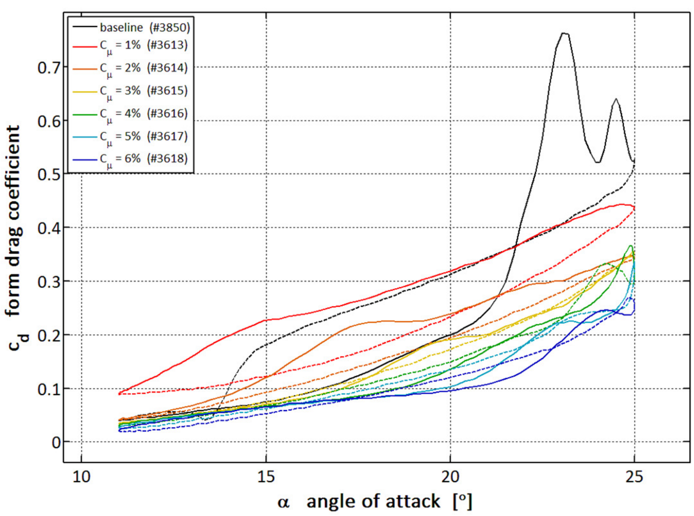
inflow: pitch **AoA:** 18°+7°sin(φ)

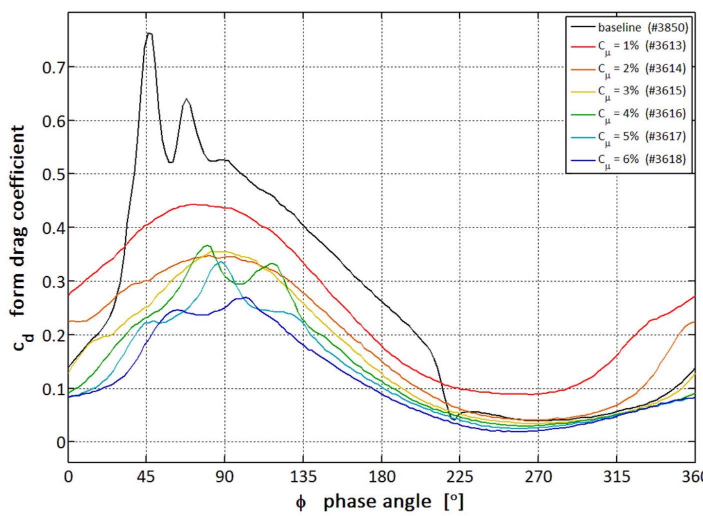








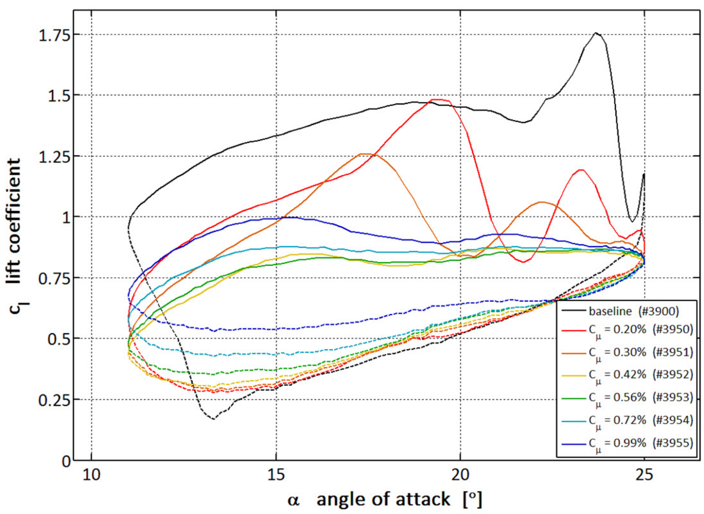


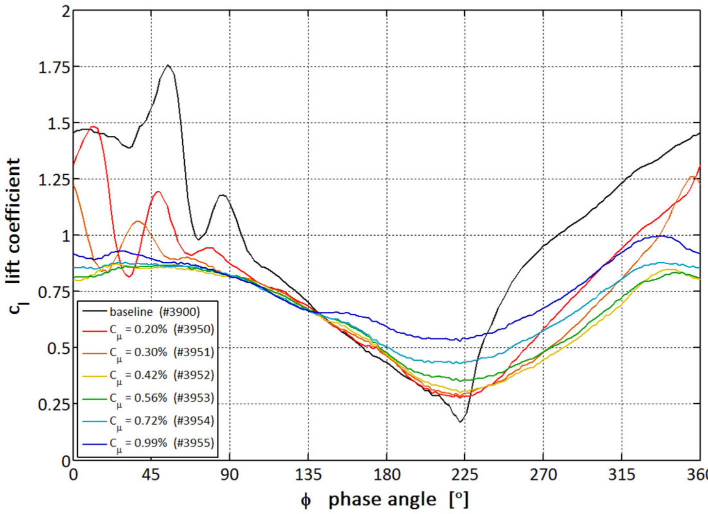


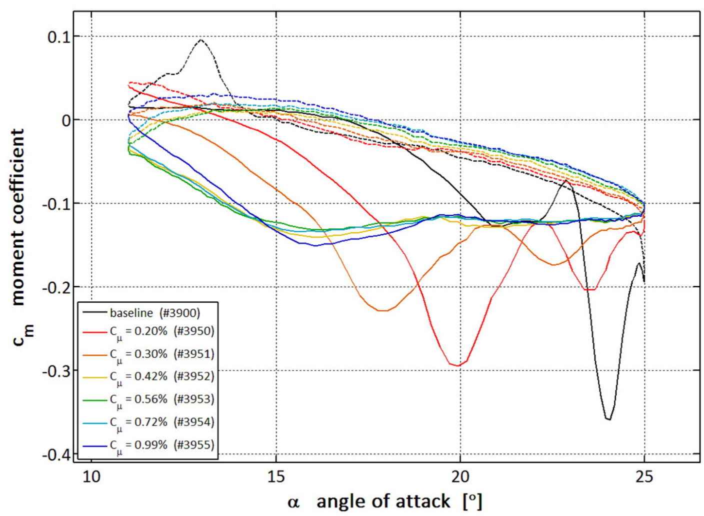
data set 99922

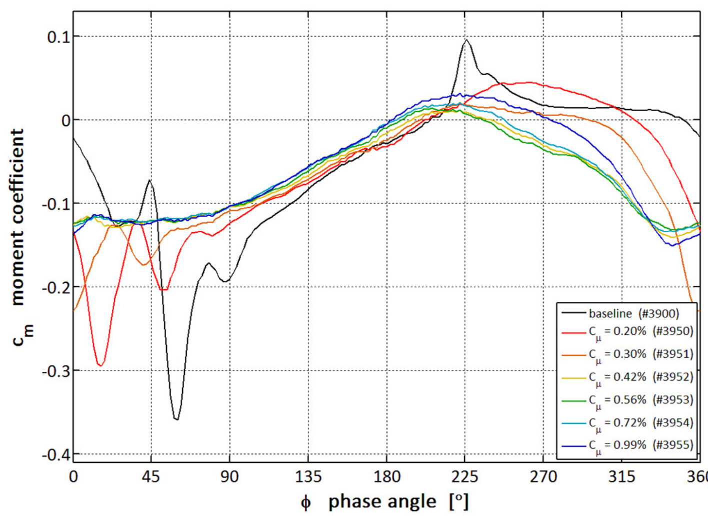
control: steady blowing **Re:** 300k **k:** 0.06

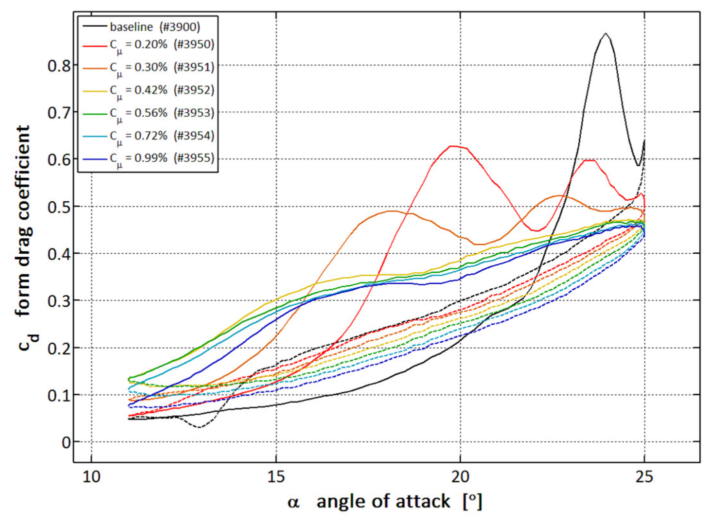
inflow: pitch **AoA:** 18°+7°sin(φ)

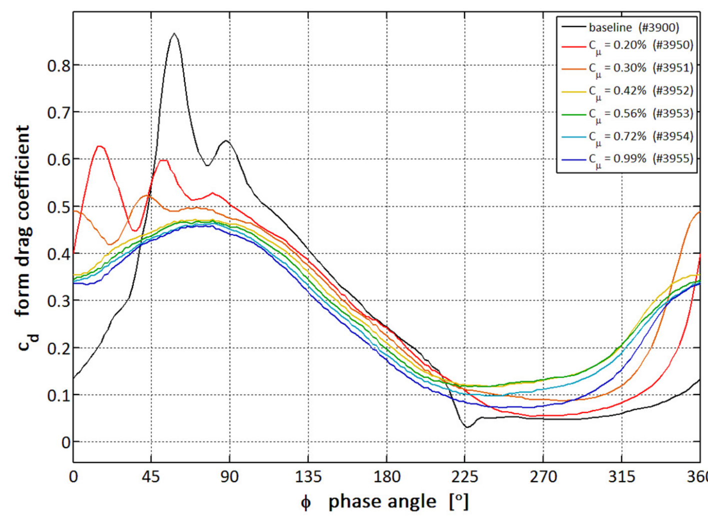








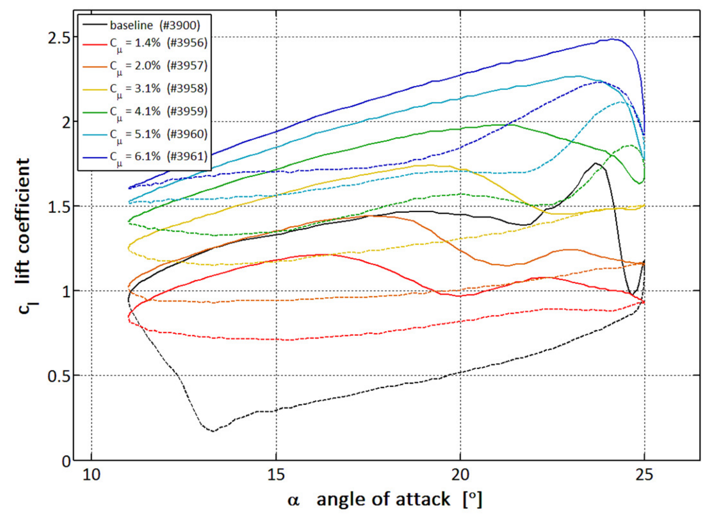


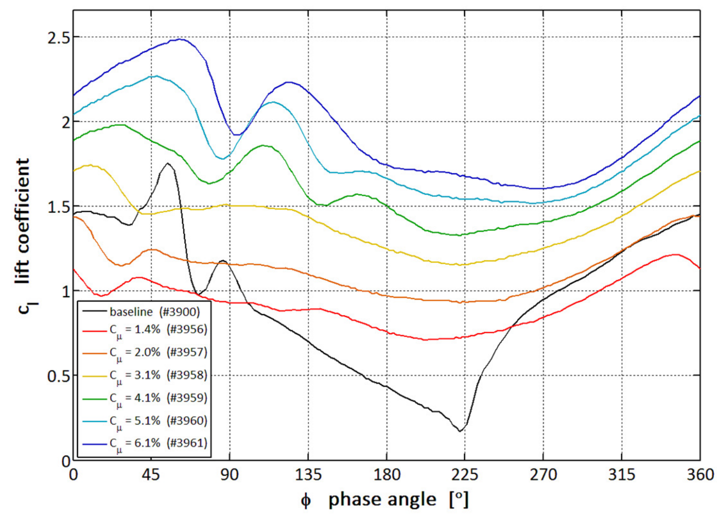


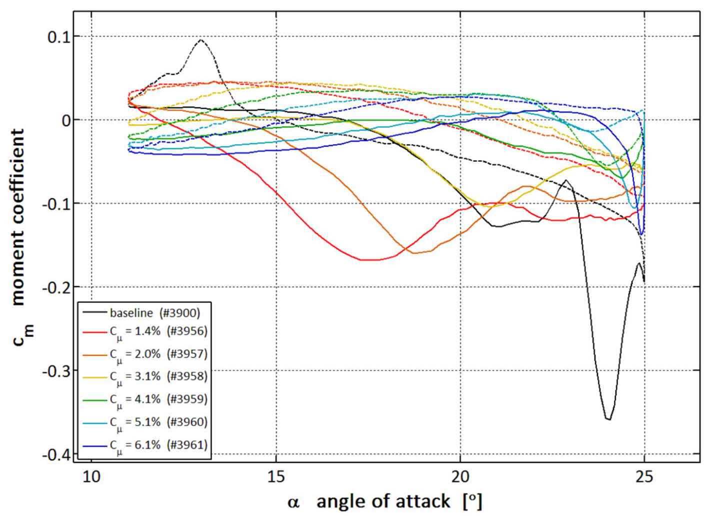
data set 99924

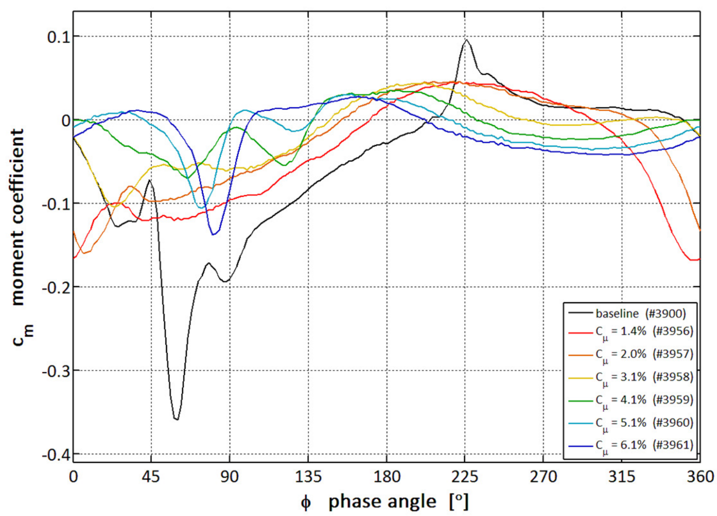
control: steady blowing **Re:** 300k **k:** 0.06

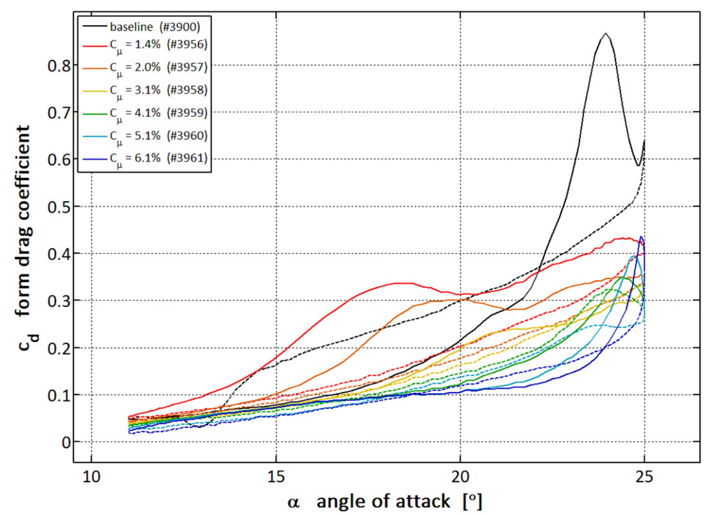
inflow: pitch **AoA:** 18°+7°sin(φ)

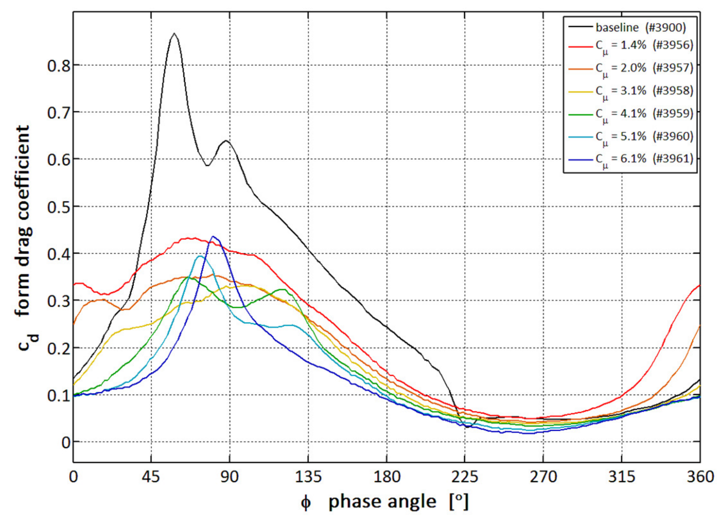






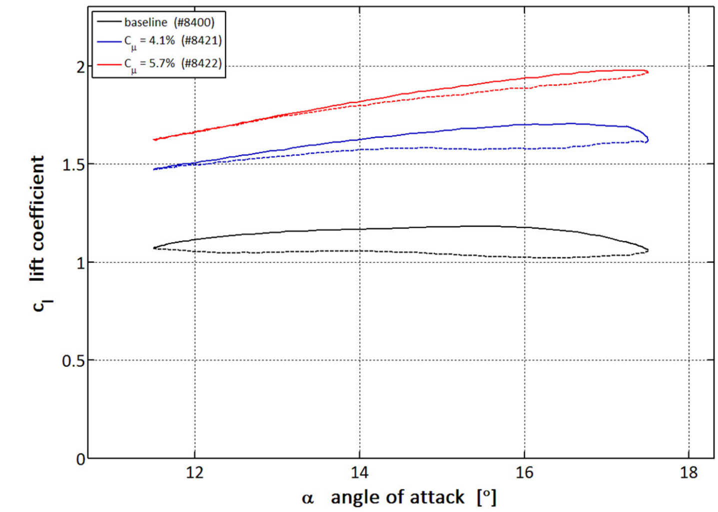


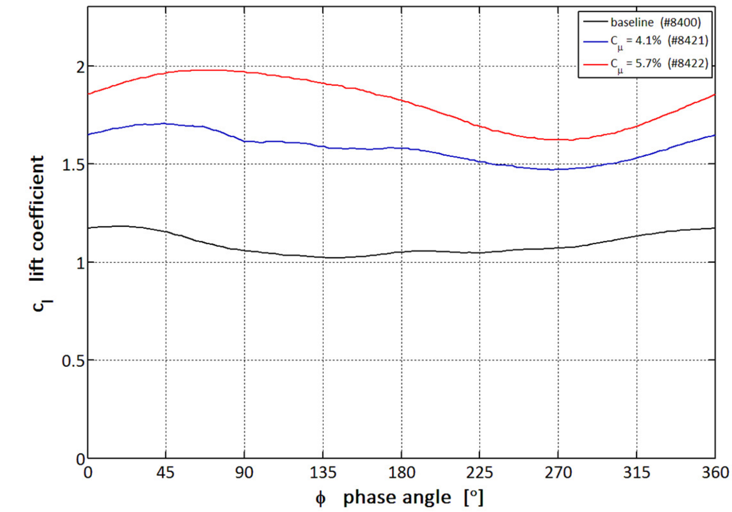


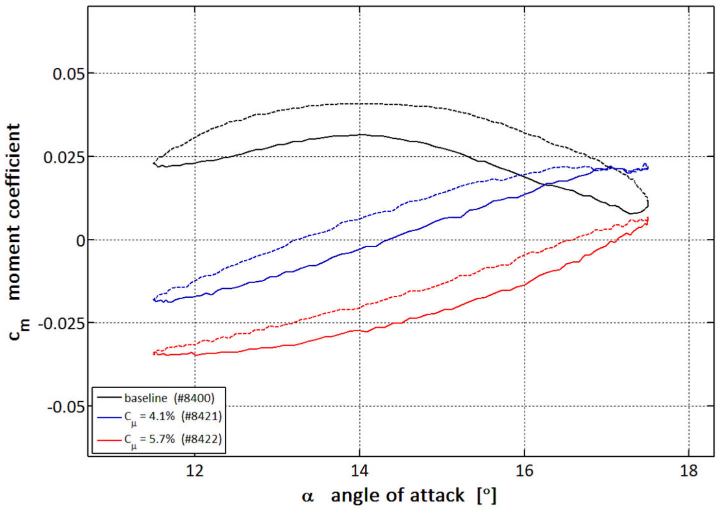


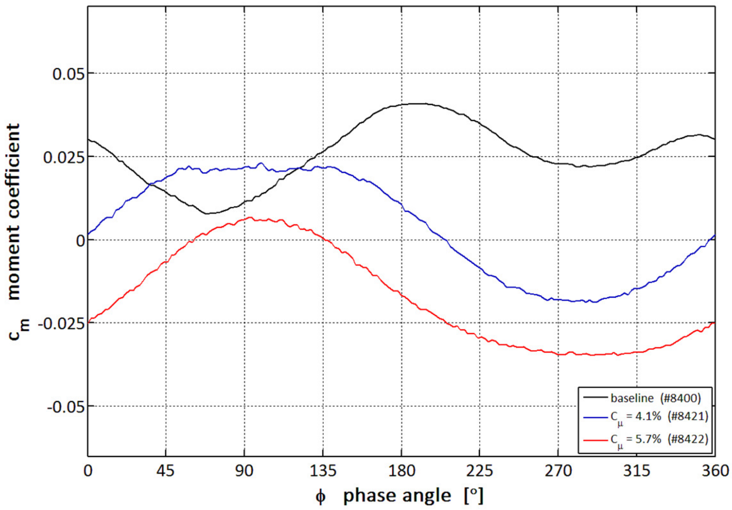
data set 99926

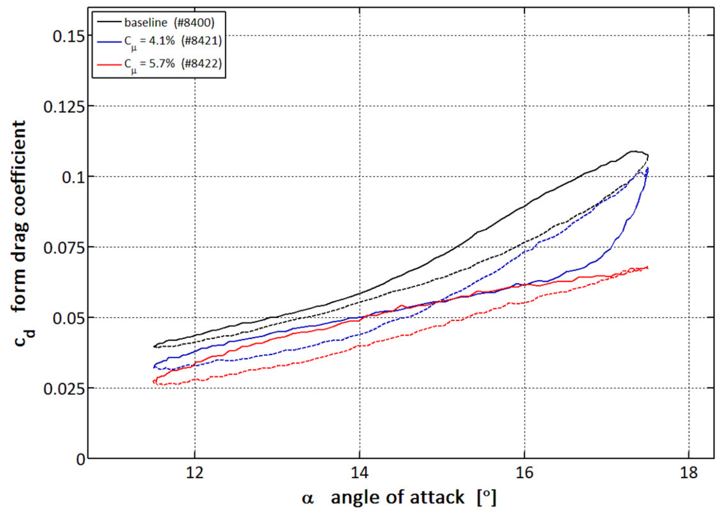
control:	steady blowing	**Re:**	300k	**k:**	0.041
inflow:	pitch	**AoA:**	14.5°+3°sin(φ)		

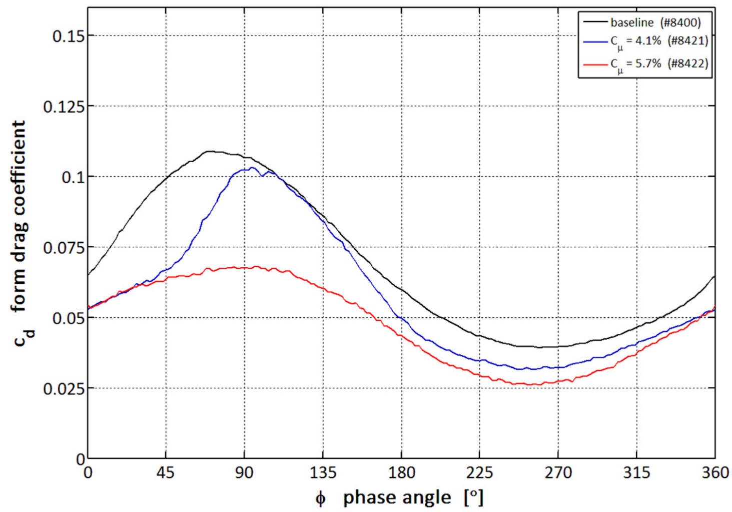








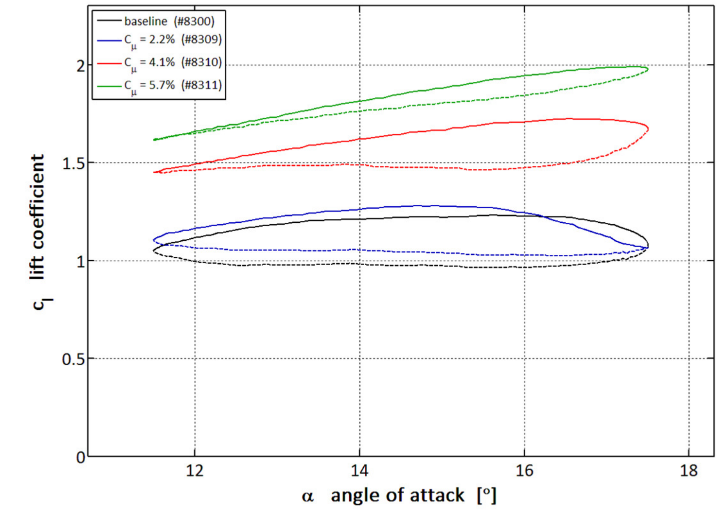


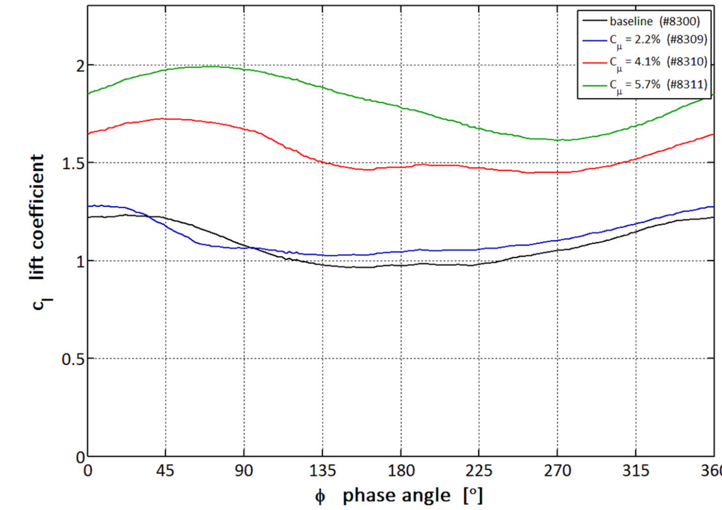


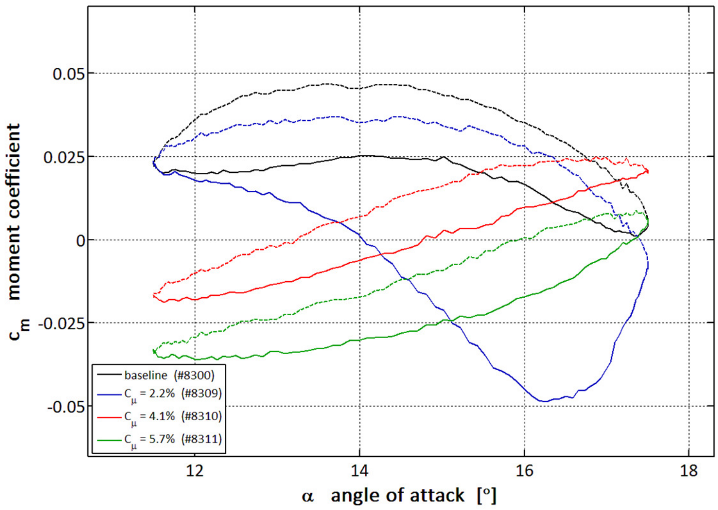
data set 99928

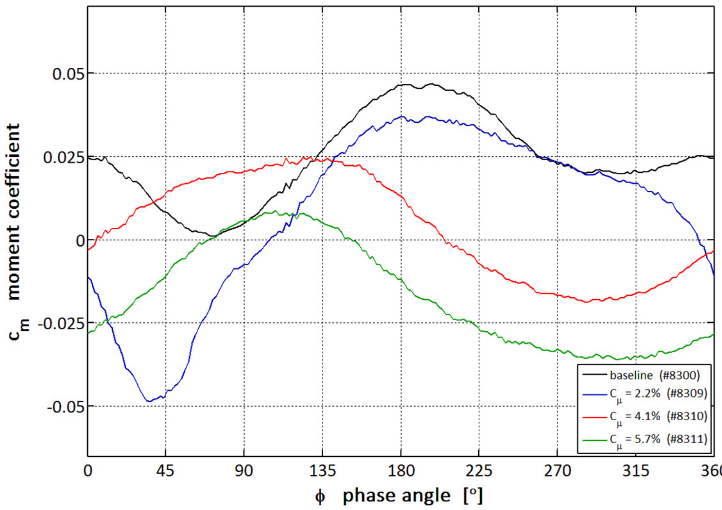
control: steady blowing **Re:** 300k **k:** 0.082

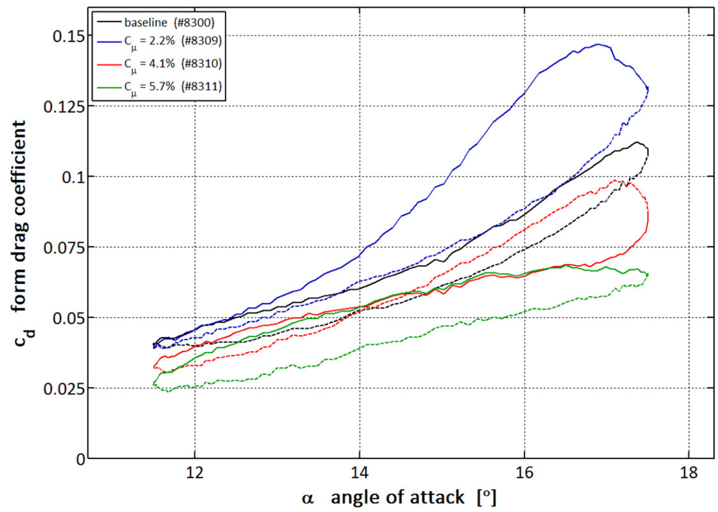
inflow: pitch **AoA:** 14.5°+3°sin(φ)

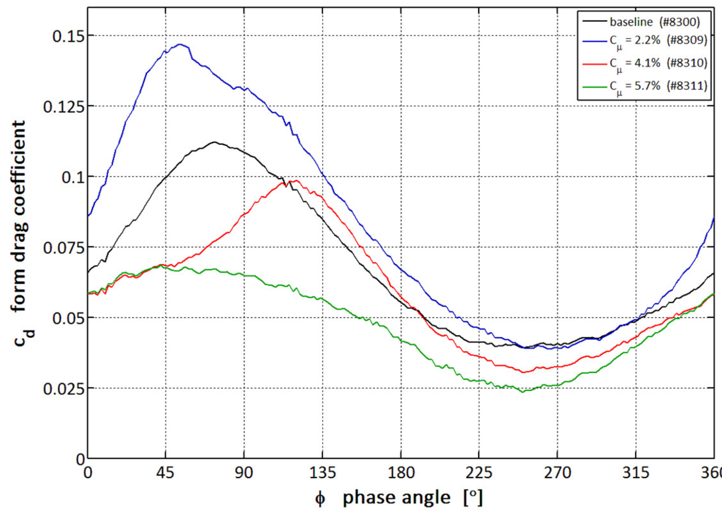








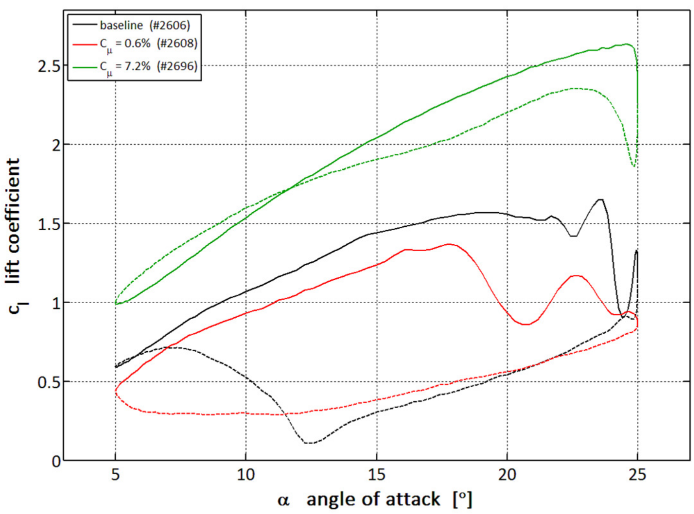


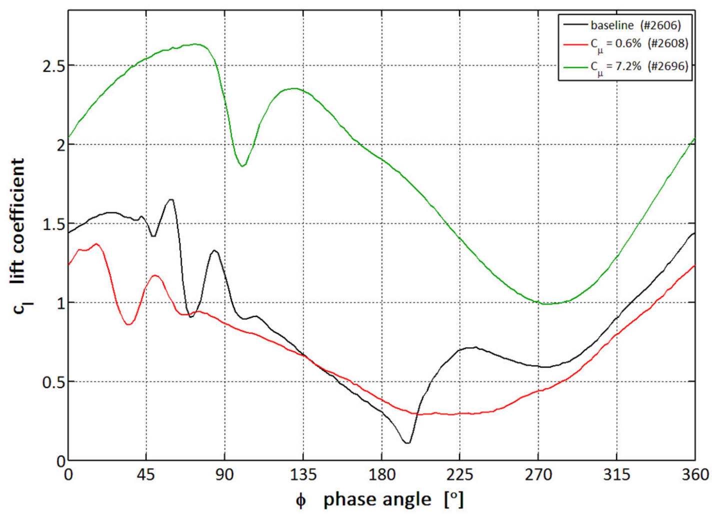


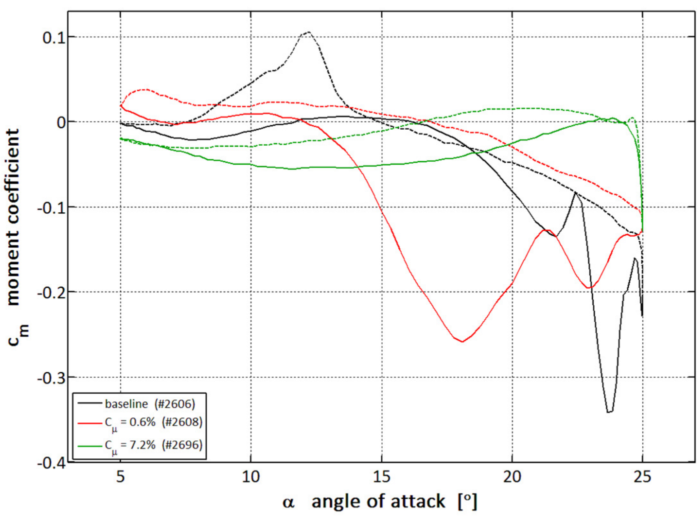
data set 99936

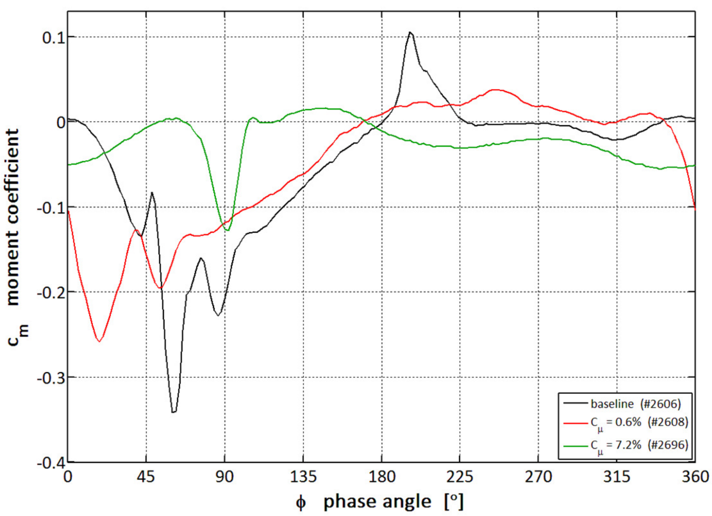
control: steady blowing **Re:** 250k **k:** 0.074

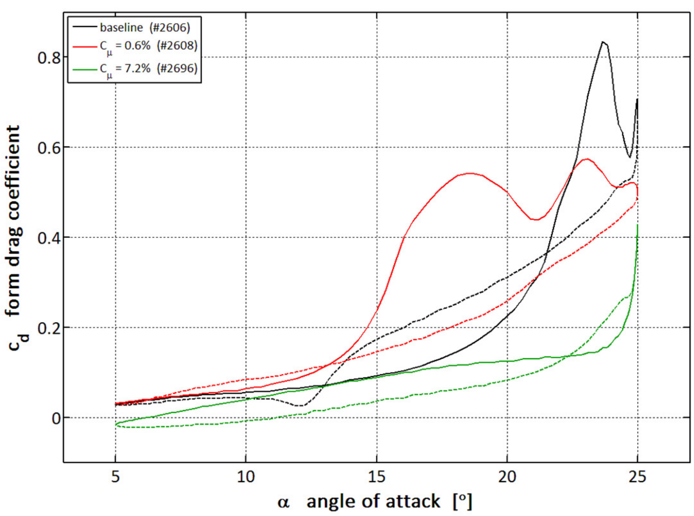
inflow: pitch **AoA:** 15°+10°sin(φ)

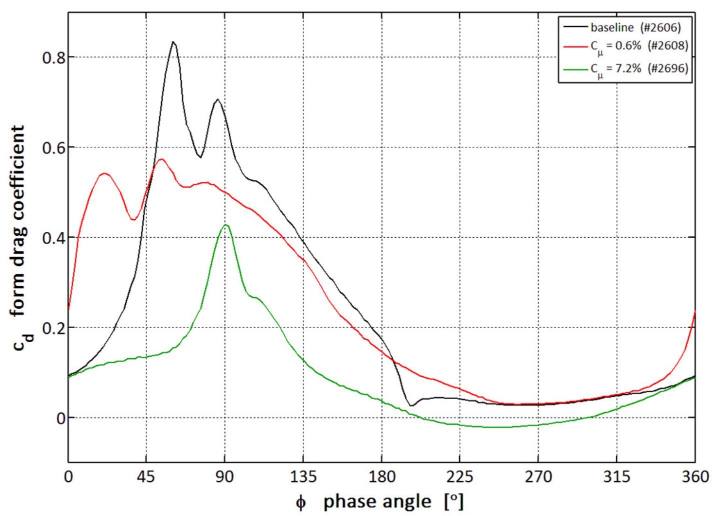






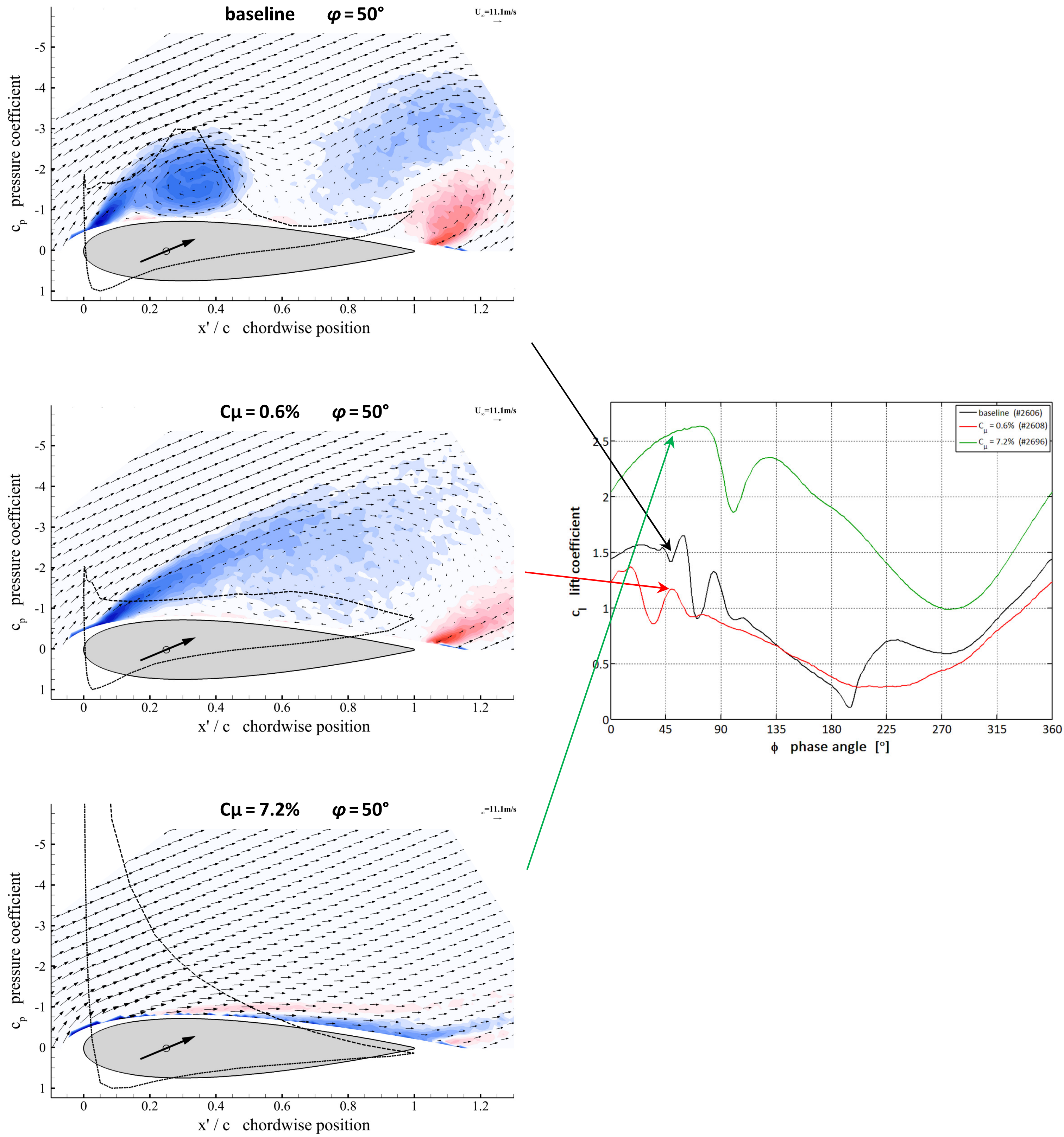






control:	steady blowing	**Re:**	250k	**k:**	0.074
inflow:	pitch	**AoA:**	15°+10°sin(φ)		

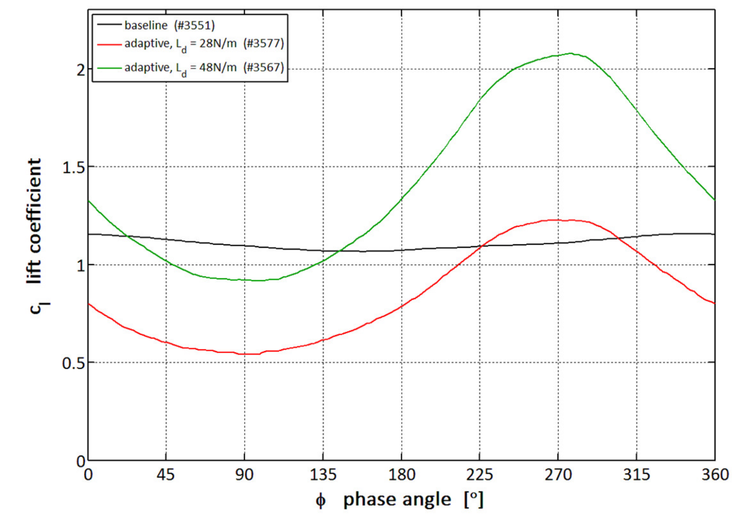
PIV data:
"FCL_PIV_data_99936.zip"

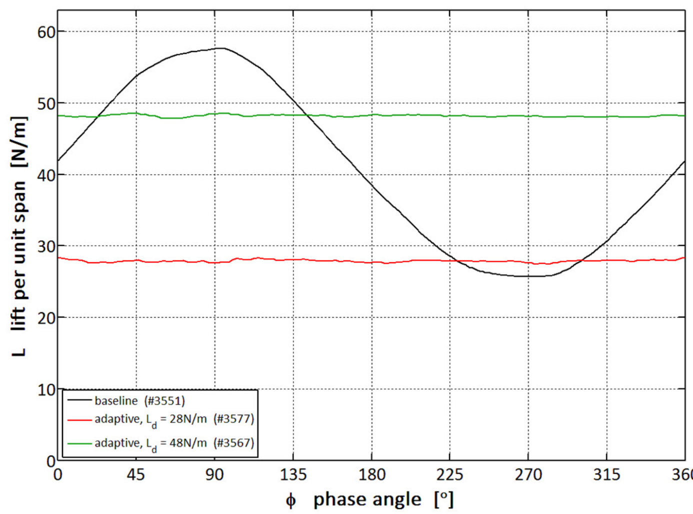


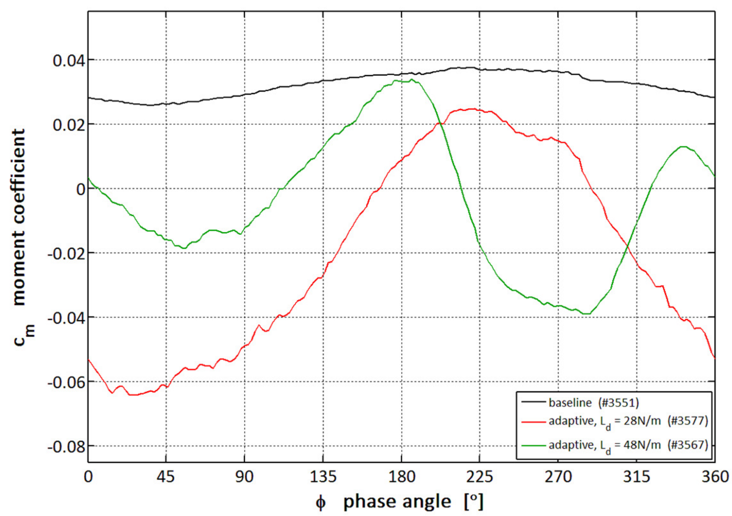
data set 99940

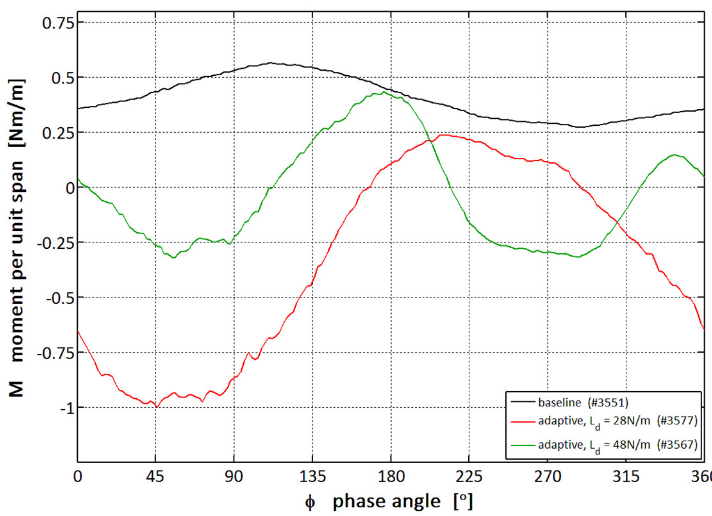
control: adaptive blowing **Re:** 300k* [1+0.2sin(φ)] **k:** 0.05

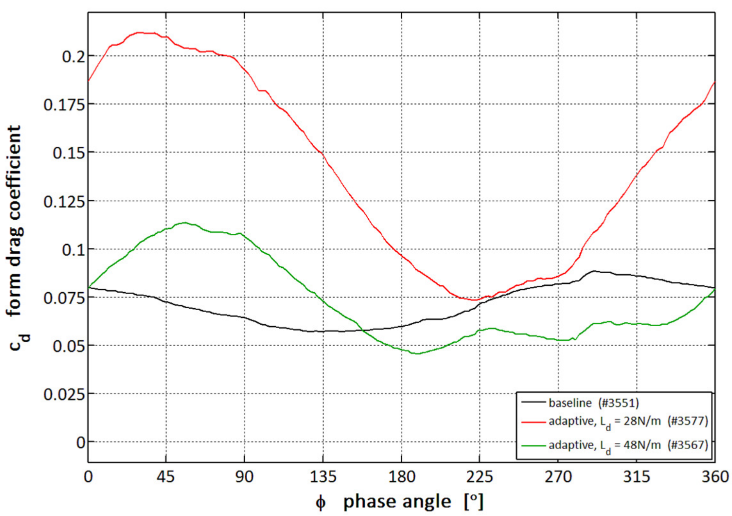
inflow: surge **AoA:** 15°







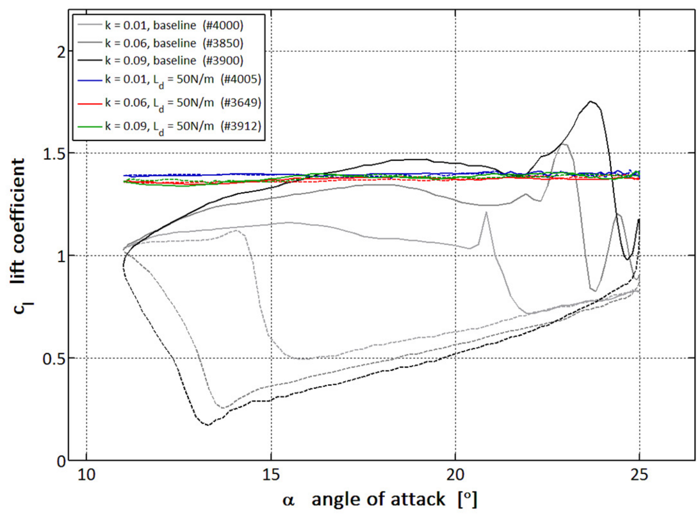


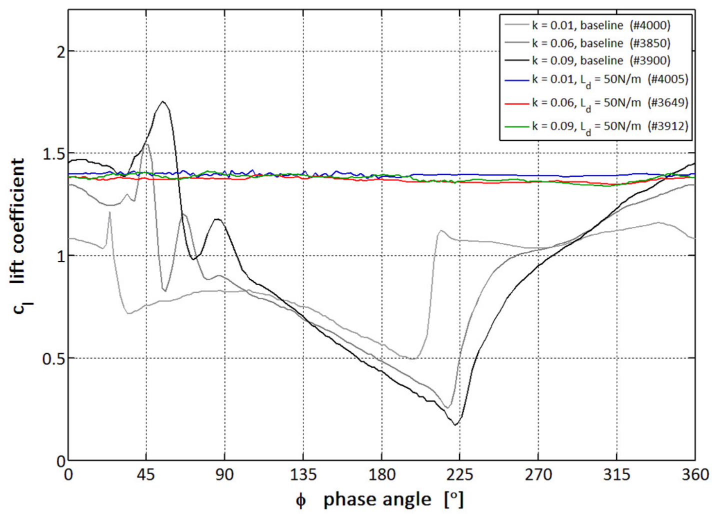


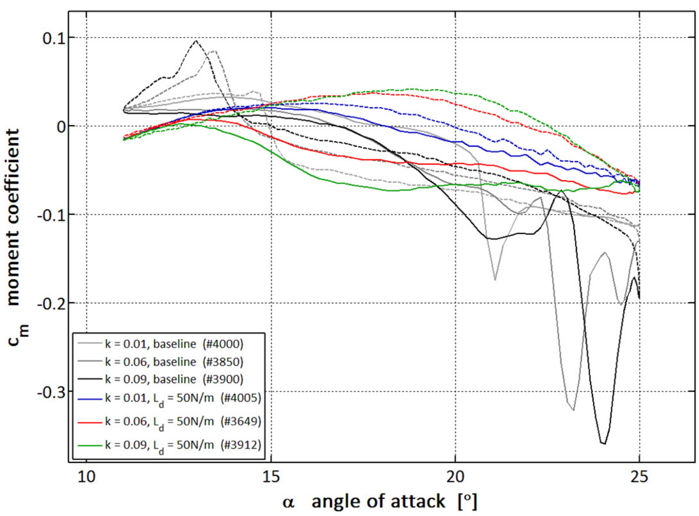
data set 99950

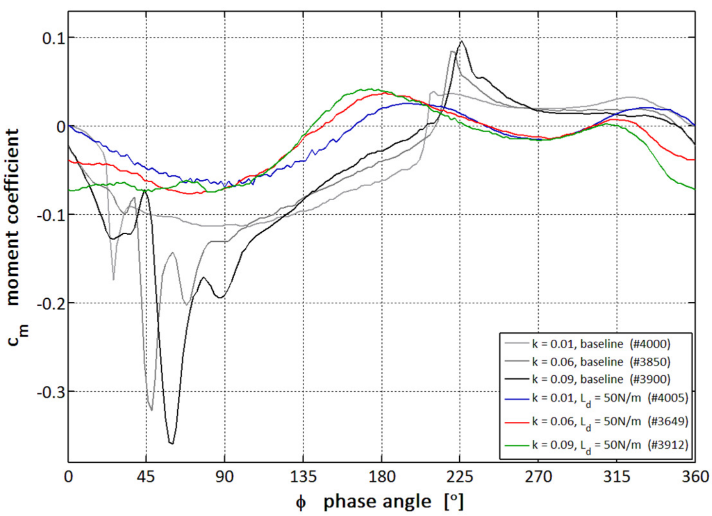
control: adaptive blowing **Re:** 300k **k:** various k

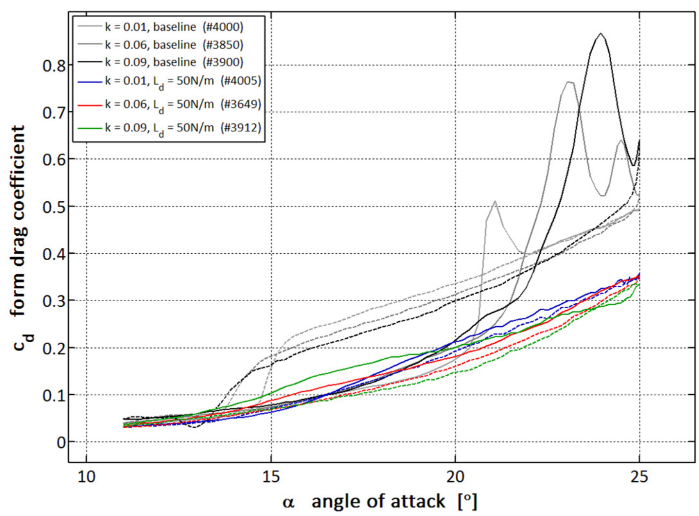
inflow: pitch **AoA:** 18°+7°sin(φ)

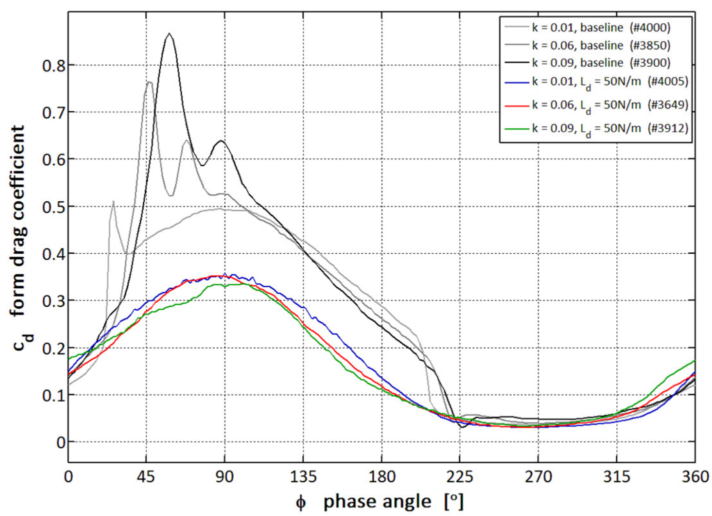








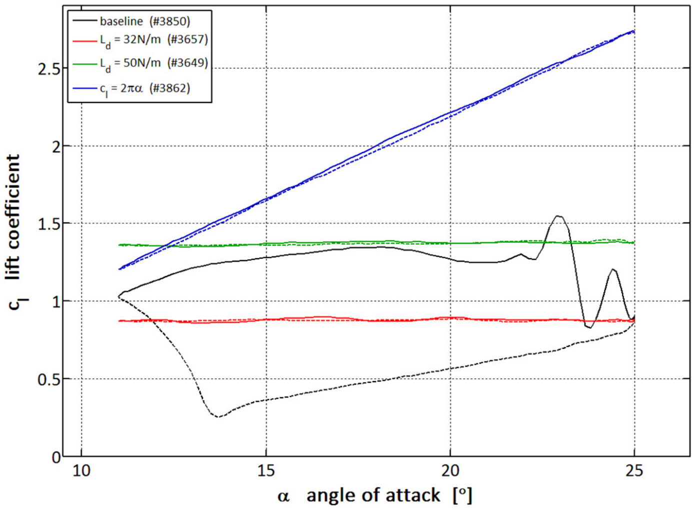


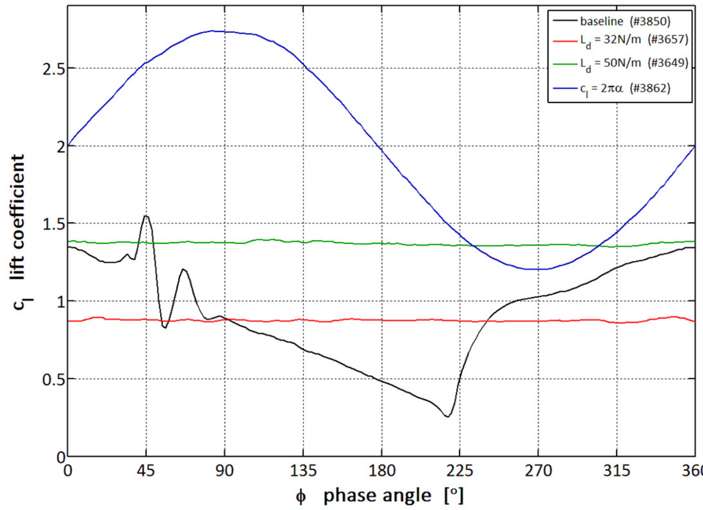


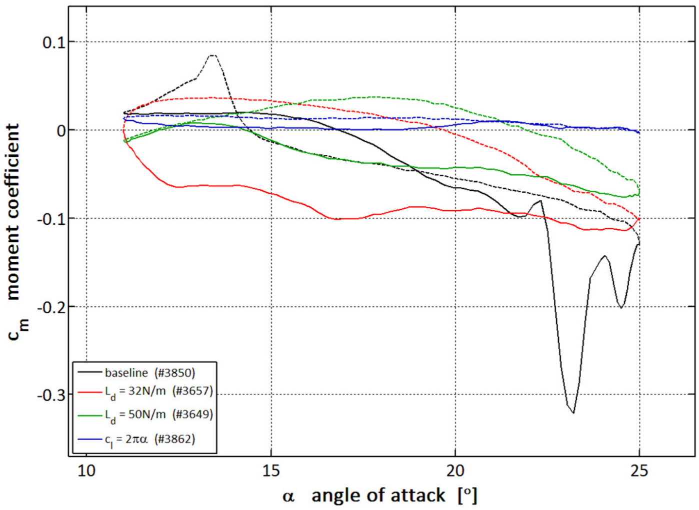
data set 99952

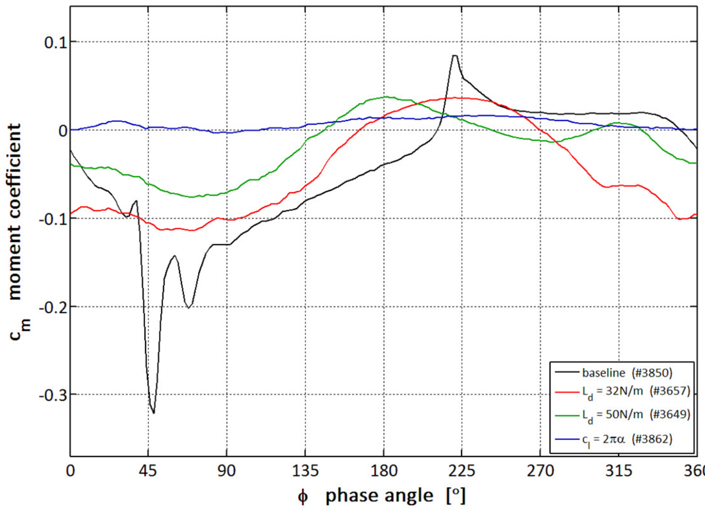
control: adaptive blowing **Re:** 300k **k:** 0.06

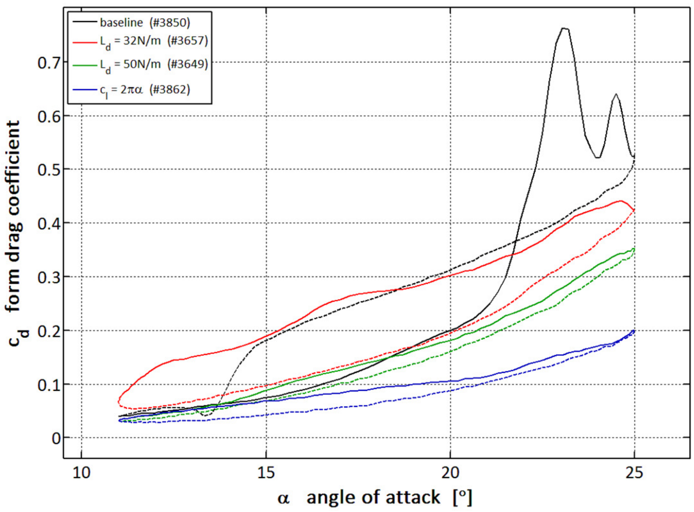
inflow: pitch **AoA:** 18°+7°sin(φ)

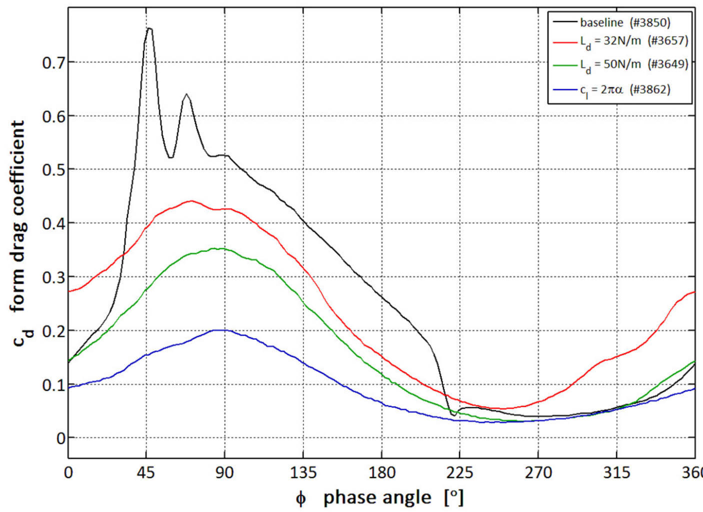








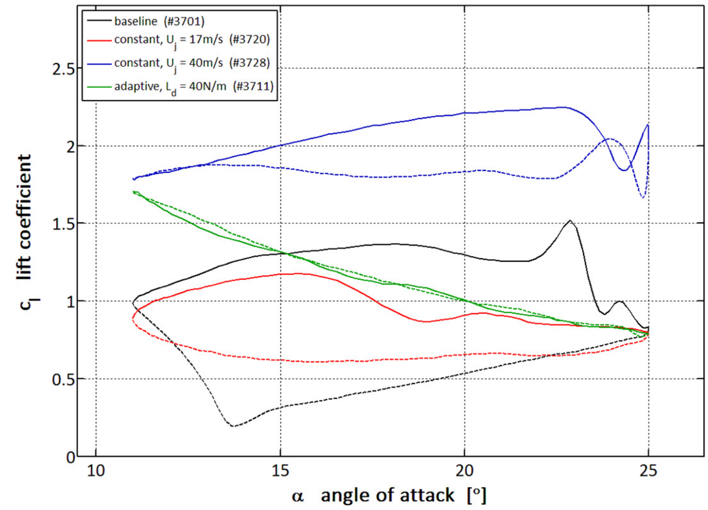


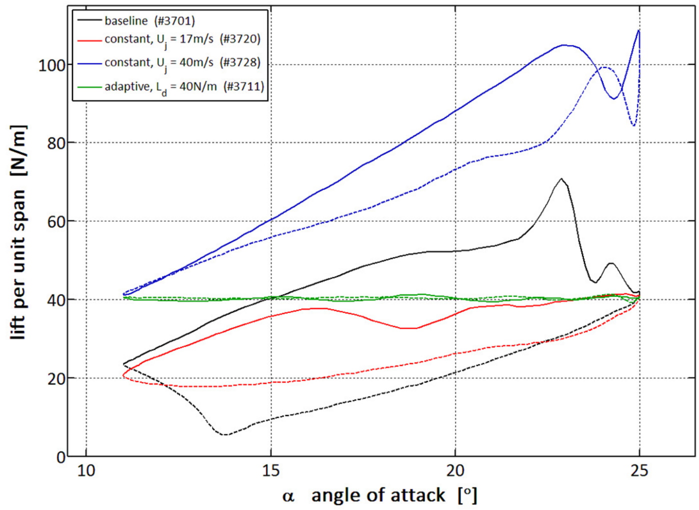


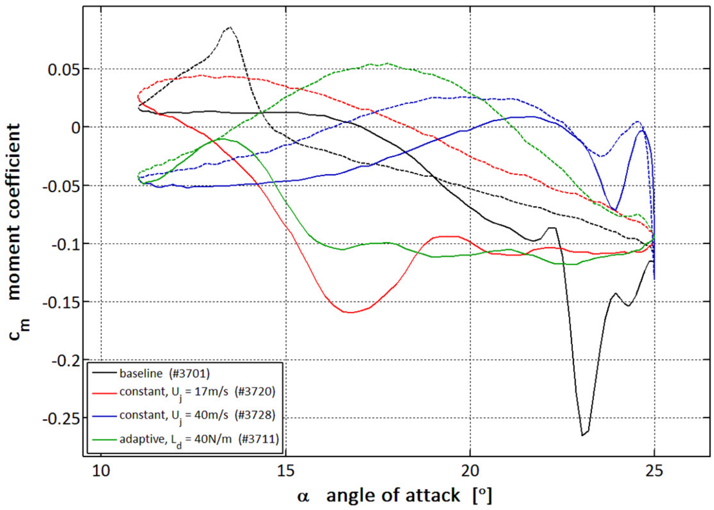
data set 99964

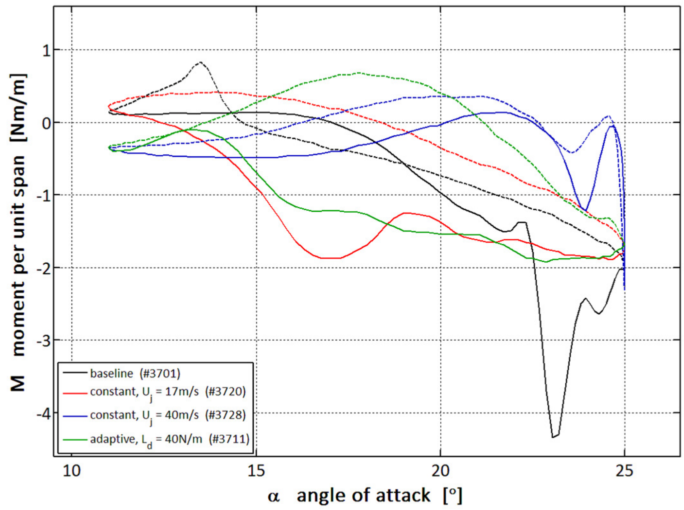
control: adaptive blowing **Re:** 300k* [1+0.2sin(φ)] **k:** 0.06

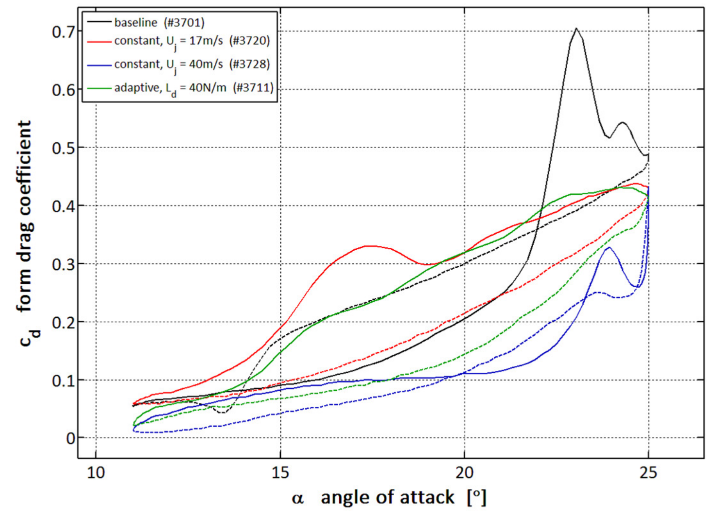
inflow: pitch & surge **AoA:** 18°+7°sin(φ)







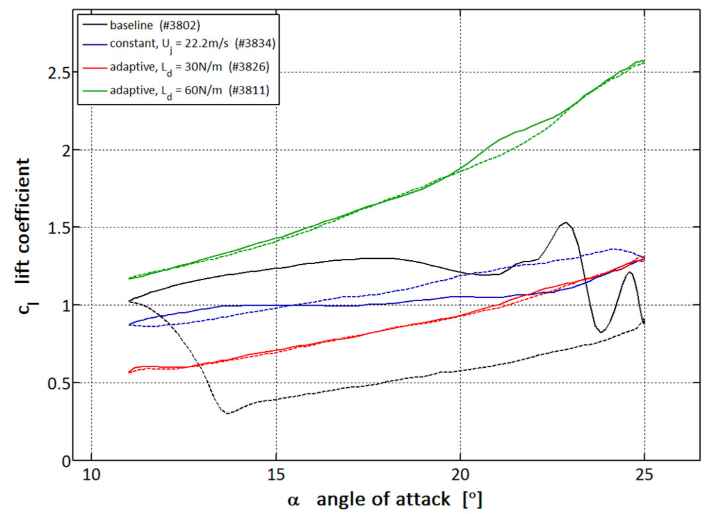


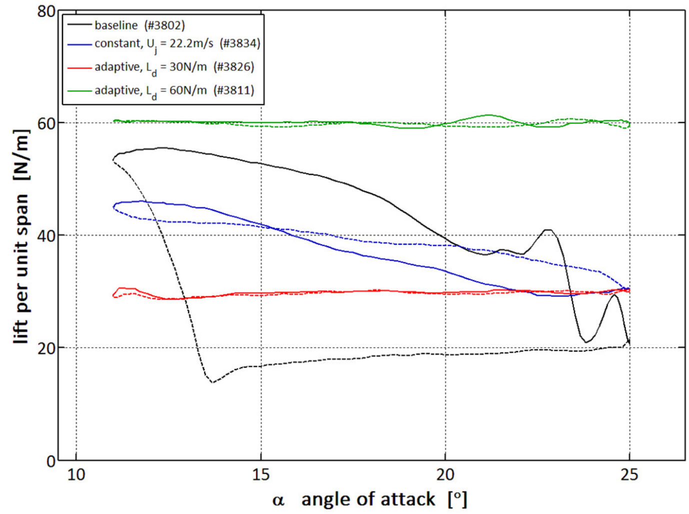


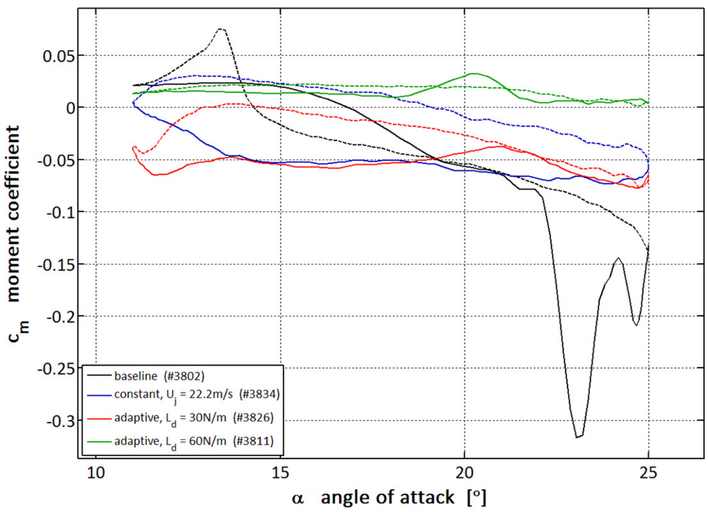
data set 99966

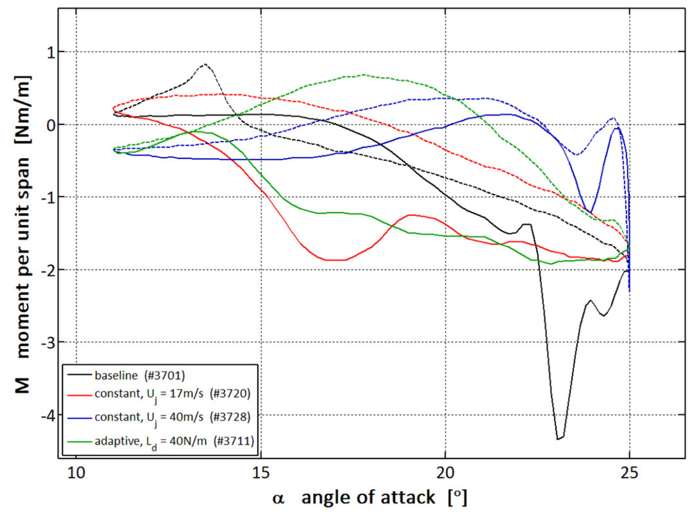
control: adaptive blowing **Re:** 300k* [1+0.2sin(φ-180°)] **k:** 0.06

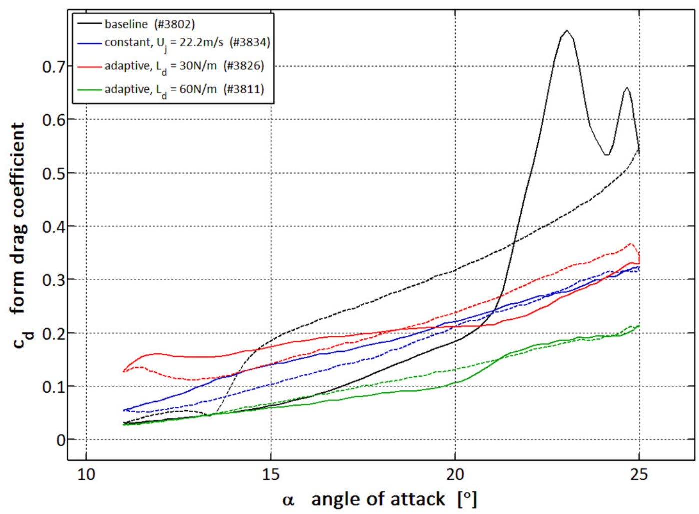
inflow: pitch & surge **AoA:** 18°+7°sin(φ)











Nomenclature

AoA	angle of attack	[°]
c	airfoil chord length	0.348m
C_d	drag coefficient	
C_l	lift coefficient	
C_m	moment coefficient	
D	drag per unit span	N/m
L	lift per unit span	N/m
M	moment per unit span	N/m^2
k	reduced frequency	$\pi fc/U_\infty$
Re	Reynolds number	$U_\infty c/\nu$
s	airfoil span	0.610m
α	angle of attack	[°]
σ	amplitude of freestream oscillations	
τ	phase shift between pitching motion and freestream oscillation	
ϕ	phase angle	[°]

Matlab variables

AoA_deg	angle of attack [°]
Cd	pressure drag coefficient
Cl	lift coefficient
Cm	moment coefficient
Cmu	momentum coefficient [%]
Cp_lower_surface	lower surface pressure coefficient
Cp_upper_surface	upper surface pressure coefficient
Uinfty_m_s	freestream velocity [m/s]
measurement_number	measurement number
phase_angle_deg	phase angle [°]
position_x_m	chordwise position of pressure port [m]
position_y_lower_surface_m	chord-normal position of pressure port [m]
position_y_upper_surface_m	chord-normal position of pressure port [m]
pressure_lower_surface_Pa	lower surface pressure distribution [Pa]
pressure_upper_surface_Pa	upper surface pressure distribution [Pa]
q_Pa	dynamic pressure [Pa]
test_case	description of test case
time_s	time [s]