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Plasma Actuation for Mitigation of Fluctuating Loads on Airfoils: An Experimental Study

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Abstract

Wind tunnel measurements are performed to investigate the potential for mitigation of aerodynamic load fluctuations on airfoils, as the main source of fatigue for wind turbines, using plasma actuators. The experiment consists of aerodynamic force measurements using six strain gauges and 2-component velocity measurements using particle image velocimetry (PIV). The analysis is focused on the aerodynamic loads, the mean flow, the turbulent kinetic energy and the proper orthogonal decomposition (POD) modes and their energy budget. The main findings are: (i) the actuation increased the lift coefficient for all the range of α, with an average and maximum increment of 0.05 and 0.1, per unit span of the actuator; (ii) the actuation deflects the airfoil near wake downward, resulting in the so-called virtual cambering effect; (iii) the actuation increases the TKE near the trailing edge, which could increase the airfoil trailing-edge noise; (iv) the POD analysis reveals that the actuation increases the size of the vortical structures in the near wake and the energy budget of the first POD modes, esp. at high angles of attack prior to stall.

1. Introduction

Unsteady loads are major constraints for upscaling of wind turbines. As the wind turbines grow in size, the blades become larger and the fatigue problem with the fluctuating loads becomes more and more serious. Active flow control has emerged as a solution to mitigate the unsteady fluctuating loads on wind turbine blades [1-3]. The level of fluctuations in lift coefficient has been quantified for a large horizontal axis wind turbine to be approximately ± 0.25 in lift coefficient at operational Reynolds numbers [4] and turbulence is identified as the major contributor to fatigue damage. Therefore, high-frequency unsteady load control will be of high interest for wind energy applications. Plasma actuator is a low power consumption, fast-response time, high-frequency and easy-to-manufacture flow control actuator that benefits from having no moving parts. On the other side, the limited magnitude of control achieved using this actuator, especially at high Re, can be its shortcomings. Due to the several advantages of this actuator, it has received growing attention for active flow control in numerous applications [5-7].

The current work investigates the influence of active load control for a symmetry airfoil using plasma actuators installed along the airfoil trailing edge using wind tunnel measurements, where high-accuracy force measurement and detailed flow velocity measurements are conducted.

The outline of the paper is as follows: section 2 presents the experimental setup and the plasma actuator settings. The results, namely the aerodynamic loads, the flow topology and the fluctuations statistics are presented in section 4 – 6. Conclusions are provided in section 7.

2. Experimental setup

A symmetric NACA64-2-A015 airfoil with modified half-rounded trailing edge is tested in A-Tunnel at TU Delft. The A-tunnel is an open-circuit low-turbulence wind tunnel. The flow speed during the experiment is 10 m/s, corresponding to a chord-based Re of 145,000. The airfoil is equipped with dielectric barrier discharge (DBD) plasma actuators operating at 40kVpp and 1.25kHz, where the actuators are positioned along the trailing-edge centerline blowing towards the pressure side of the airfoil, see Fig. 1. High-accuracy force measurements using 4 strain-gauge are performed at 50 Hz. The flow velocity is measured using planar (2D) particle image velocimetry (PIV), see Fig. 2.

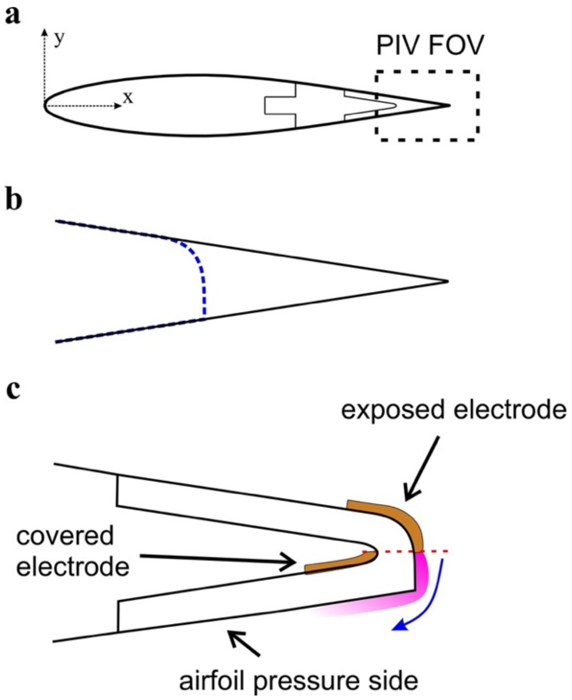

Figure 1. Schematic of (a) PIV field of view (FOV); (b) original sharp edge trailing edge vs the modified half-rounded; (c) he plasma actuator electrodes along the trailing edge.

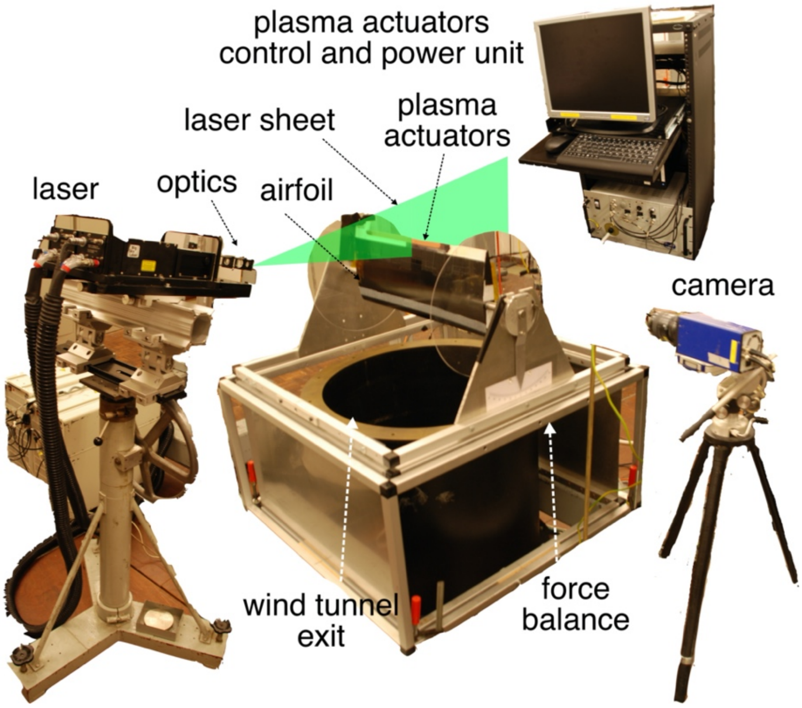

Figure 2. Schematic of the PIV setup.

3. Aerodynamic loads

Fig. 3 shows lift and drag coefficients for airfoil with plasma actuator off and on. Fig. 4 shows the change in lift coefficient per unit span of the actuator due to plasma actuation versus angle of attack. The main findings are:

- The actuation increases the lift coefficient over the whole range of angle of attack prior to stall.
- The increase in lift coefficient results in a drag penalty. The drag increment remains almost the same over the whole range of angle of attack prior to stall.
- The average lift increment per unit span of the actuator is 0.05. This reduces at moderate angles of attack, near 10°, and reaches a maximum of 0.1 prior to stall at 14°.

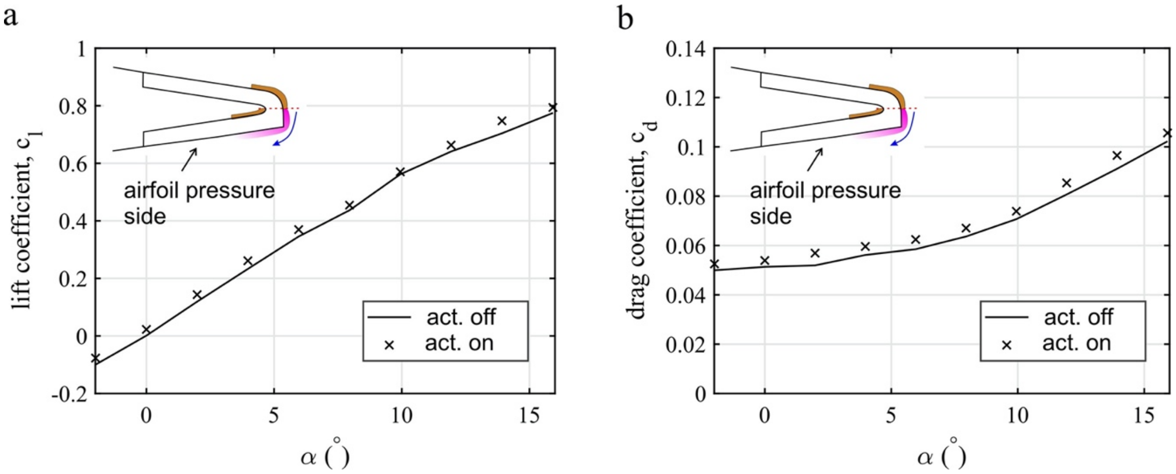

Figure 3. Lift and drag coefficients for airfoil for plasma actuator off and on. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%.

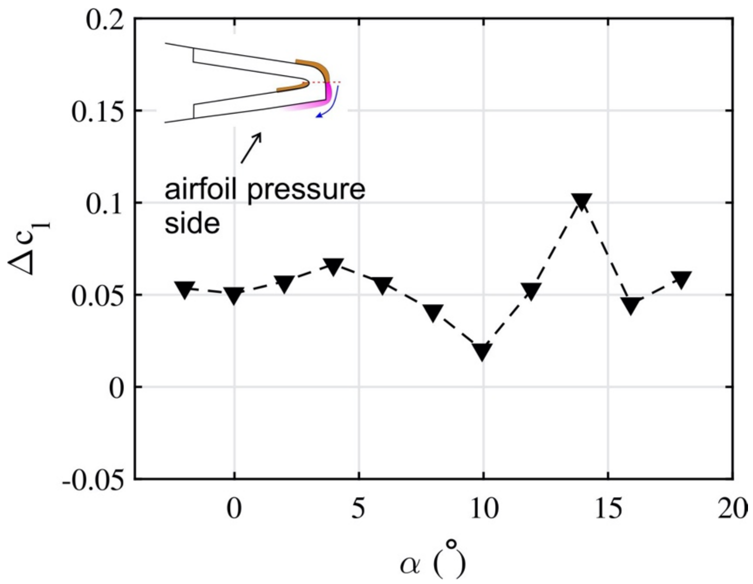

Figure 4. Change in lift coefficient per unit span of the actuator due to plasma actuation versus angle of attack. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%.

4. Flow topology

Fig. 5 shows the contour plots of time-averaged normalized streamwise velocity with superimposed streamlines for actuator on and off. Fig. 6 shows the time-averaged velocity profiles in the airfoil near wake at zero angle of attack. Fig. 7 shows the airfoil wake deflection angle due to the plasma actuation for different angles of attack, α = 0°, 5°, 10°, 12°, 14° and 16°. Note that the plasma actuator is positioned at the trailing-edge centerline, see Fig. 1, with a momentum efficiency of 0.3%.

Based on Fig. 5 – 7, the following observations are made:

- The actuation results in significant increase in velocity magnitude in the airfoil near wake.

- At zero angle of attack, the actuation minimally affects the recirculation region just downstream of the trailing edge. Due to the actuation, the two parts of the recirculation region are made the same size and the recirculation zone is slightly enlarged.
- Due to the actuation, the airfoil near wake is deflected downward. This is the so-called virtual cambering effect, which results in an increase of the lift coefficient for a penalty in drag coefficient.
- The trend of the downward wake deflection angle is in line to the trend already observed for the change in lift coefficient. Minimal values of wake deflection angle correspond to the moderate angles of attack while the highest values of the wake deflection angle correspond to high angles of attack just prior to stall.

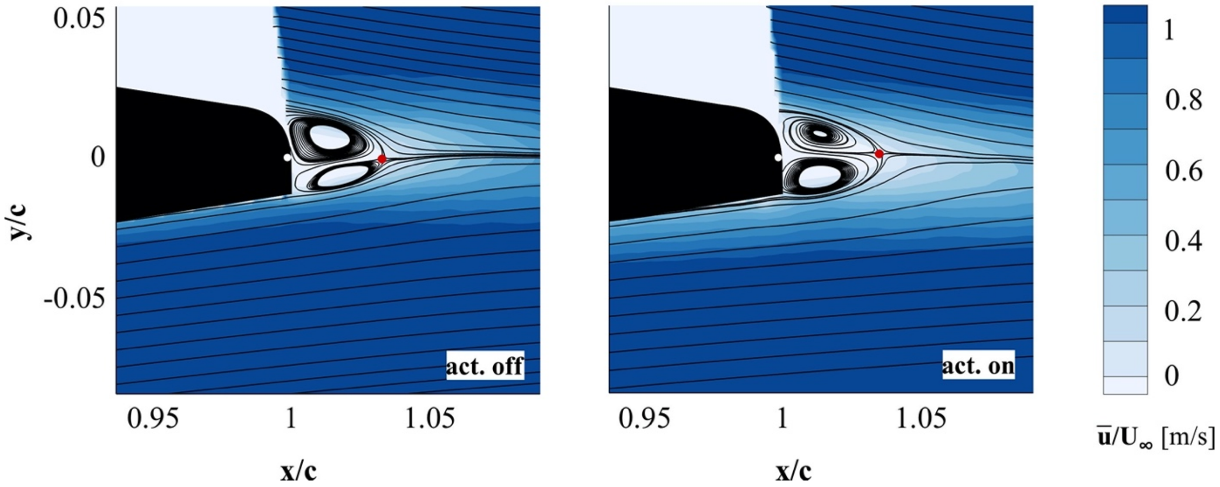

Figure 5. Contour plots of time-averaged normalized streamwise velocity with superimposed streamlines for actuator on and off. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%. Position of the plasma onset is shown using a white circle.

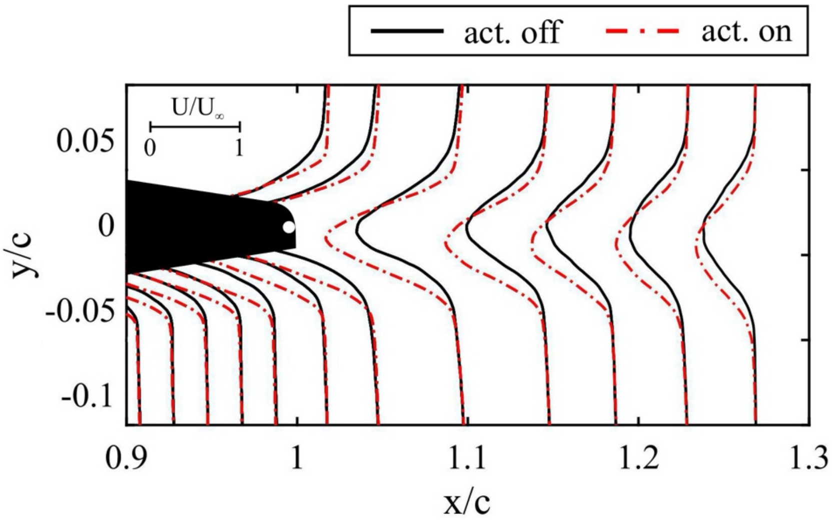

Figure 6. Time-averaged velocity profile in the near wake at zero angle of attack. Position of the plasma onset is shown using a white circle. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%.

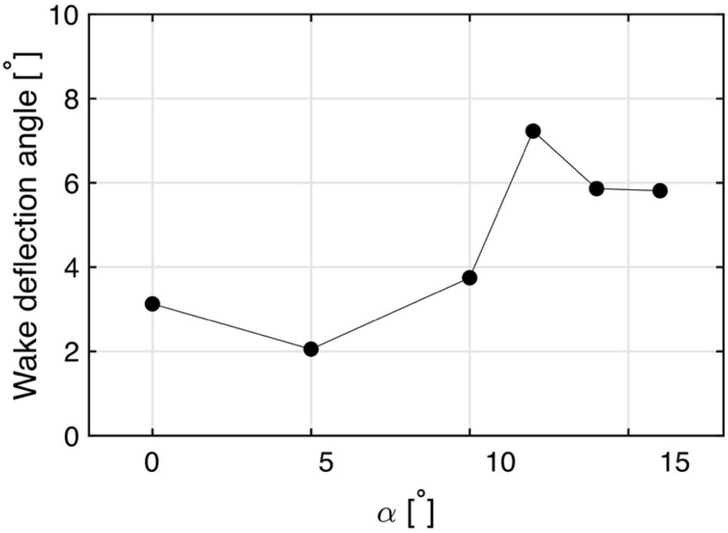

Figure 7. Wake deflection angle due to plasma actuation for different angles of attack. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%.

5. Fluctuations statistics

Fig. 8 shows the contour plots of turbulent kinetic energy (TKE) for two different angles of attack, α = 0° and 12°. Fig. 9 shows the contour plots of dimensionless vorticity of the 1st proper orthogonal decomposition (POD) mode at the same angles of attack in the near wake. Fig. 10 shows the fluctuating energy budget for the first 8 POD modes for the actuator off and on at different angles of attack, α = 0°, 5°, 10° and 12°. Note that the plasma actuator is positioned at the trailing-edge centerline, see Fig. 1, with a momentum efficiency of 0.3%.

Based on Fig. 8 – 10, the following observations are made:

- At low angles of attack, α = 0°, insignificant influence of plasma actuation on TKE in the airfoil near wake is found.
- At high angles of attack prior to stall, α = 12°, plasma actuation increases TKE near the airfoil trailing-edge centerline. In addition, the region of high TKE is shifted closer to the airfoil trailing edge due to the plasma actuation. This would lead to an increase of trailing-edge noise and structural vibrations, which needs to be considered.
- The actuation increases the size of the vortical structures in the near wake in addition to shifting them closer to the trailing edge. This is more significantly pronounced at high angles of attack prior to stall, α = 12°.
- The actuation increases the energy budget of the first 2 POD modes. This energy increase corroborates the growth in the size of the coherent structures. The magnitude of the energy increase is minimal at moderate angles of attack and is maximum at high angles of attack prior to stall, α = 12°.

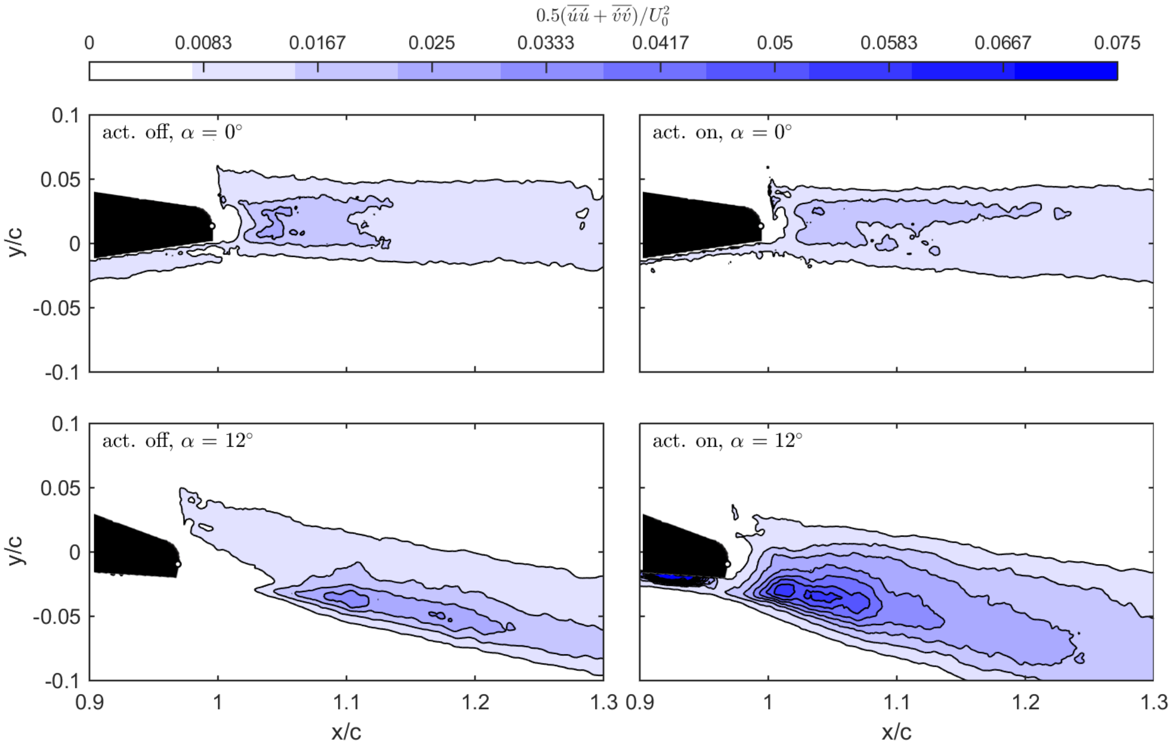

Figure 8. Contour plots of turbulent kinetic energy for two different angles of attack. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%. Position of the plasma onset is shown using a white circle.

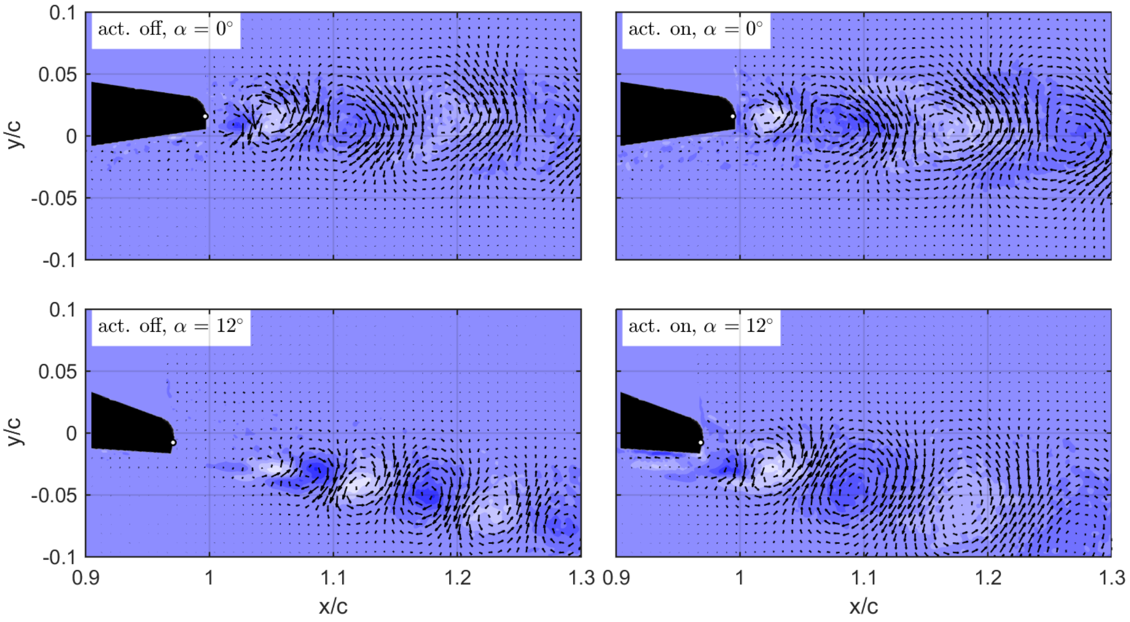

Figure 9. Contour plots of dimensionless vorticity field of the 1st POD mode at two different angles of attack. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%. Position of the plasma onset is shown using a white dot.

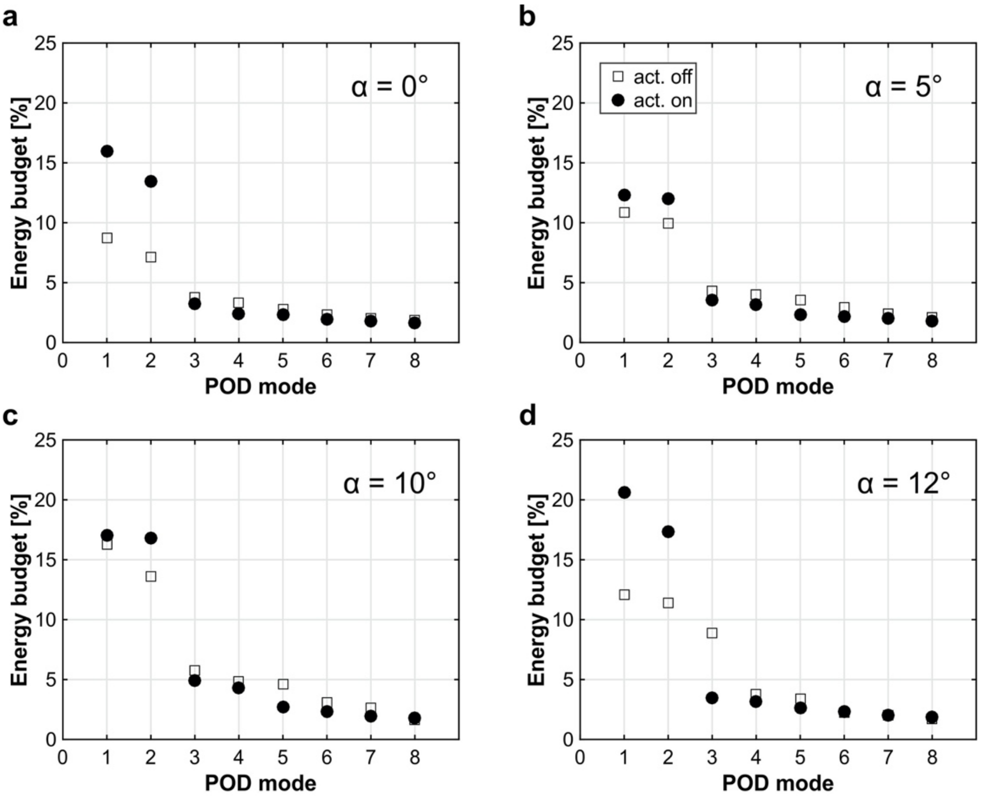

Figure 10. Fluctuating energy budget for the first 8 POD modes for actuator off and on at different angles of attack. The actuator is positioned at the trailing-edge centerline with a momentum efficiency of 0.3%.

6. Discussion

In this work, POD analysis is performed using 2D PIV data. In principle, POD can be applied even to a single-component velocity data measured at minimum 2 points. In that case, the dataset would be 2-dimensional, and POD would properly decompose the dataset into 2 orthogonal modes. For 2D PIV with a data size of $Nx \times Ny$, the problem would be n-dimensional, where $n = 2 \times Nx \times Ny$. POD will then properly decompose the dataset into n orthogonal modes. This decomposition aims to identify a limited number of most energetic modes, i.e. the dominant coherent structures. Note that as the 2D PIV data contains the streamwise and lateral velocity components along the airfoil mid-plane, the POD could thus identify the coherent "spanwise" structures. In case, tomographic (3D) PIV data was available, the POD could additionally identify the coherent "streamwise" structures, where, as obvious, this is not possible with 2D PIV.

As shown in Fig. 8, the plasma actuation results in an increase in the TKE in the near wake, which can cause noise and structural vibrations. However, the generated noise is thought to be comparatively low in magnitude, compared to other sources of noise of the global system, e.g. wind turbines. To solidify this reasoning, further research is proposed [8]. Regarding the vibration, as the actuator aims to alleviate the unsteady load fluctuations, this will not be an issue.

7. Conclusions

An experimental investigation is performed to analyze the influence of plasma actuation near the (half-rounded) trailing edge of an airfoil on the aerodynamic loads to seek potentials for active load control using plasma actuators. Particle image velocimetry (PIV) is also performed to study the near wake flow to understand the underlying physics. The main conclusions are:

Aerodynamic loads:

- The actuation increases the lift and drag coefficient over the whole range of studied angle of attack prior to stall.
- The average lift increment per unit span of the actuator is 0.05. This reaches a maximum of 0.1 at 14°.

Flow topology:

- The actuation deflects the airfoil near wake downward, i.e. the virtual cambering effect.
- The actuation increases the local velocity magnitude in the near wake.

Fluctuations statistics:

- TKE: The actuation increases the TKE near the trailing edge and move the high TKE region closer to the trailing edge, esp. at high angles of attack prior to stall.
- POD: The actuation increases the size of the vortical structures in the near wake and the energy budget of the first POD modes, esp. at high angles of attack prior to stall.

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