International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:1, 2015

# Experimental and Numerical Investigation of Flow Control Using a Novel Active Slat

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*Abstract*—An active slat is developed to increase the lift and delay the separation for a DU96-W180 airfoil. The active slat is a fixed slat that can be closed, fully opened or intermittently opened by a rotating vane depending on the need. Experimental results show that the active slat has reduced the mean pressure and increased the mean velocity on the suction side of the airfoil for all positive angles of attack, indicating an increase of lift. The experimental data and numerical simulations also show that the direction of actuator vane rotation can influence the mixing of the flow streams on the suction side and hence influence the aerodynamic performance.

*Keywords*—Active slat, flow control.

## I. Introduction

ACTIVE flow control plays an over increasing part in aerodynamics research as the conventional aerodynamic design are pushed to their limits [1]. Flow control is pursued to increase the aerodynamic performance envelope by delaying stall and increasing lift. Such measures can lead to reduced takeoff distances, less fuel consumption, and increased power production in case of wind turbine blades.

Successful flow control has been demonstrated in the past by use of oscillatory synthetic jets [2], [3], dielectric barrier discharge [4] and several other lab oriented techniques. For all active flow techniques the actuation frequency, actuation amplitude and location play a critical role for the success of the technique [5], [6], [1], [3]. The role of the frequency can be easily assessed in the laboratory, since it is more or less acknowledged that the most effective frequency corresponds to the frequencies related to the hydrodynamic instabilities of the shear layer. The effect of the amplitude is difficult to assess since each technique excites the shear layer differently. For synthetic jets, the oscillatory suction and blowing trigger mixing in the shear layer, whereas for dielectric barrier discharge the induced jets and vorticies on the surface trigger the mixing. While it is possible to test both these techniques in the laboratory, it is very difficult to generate the required suction/blowing oscillatory amplitudes and electric voltages needed for enhanced mixing of a large scale airfoil. To this end, a new novel active slat is proposed that is easily implemented in any airfoil since it requires simple mechanical actuation and a fixed non-deforming airfoil profile. To increase the usefulness of this research, the DU96-W180 airfoil was selected since it is a common airfoil used in the wind turbine industry and the flow Reynolds number is typically lower than that used in commercial aircrafts.

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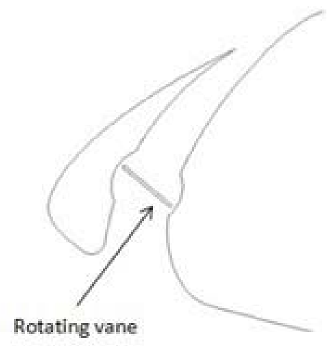



Fig. 1 Modeling of a rotating valve actuation in active slat

To determine the appropriate location to apply active flow control a numerical approach must be pursued [6], [7] because experimentally the design space would be too large to test. In this paper the numerical model was tested and compared with experimental results to proceed in further studies to optimize the location of the active slat.

## II. Experimental Setup

### A. Actuator Design

In this paper a novel actuator is designed that is both scalable and efficient for large full scale airfoils. The blowing on the upper surface of the airfoil is achieved by using an ”active slat” as shown in Fig. 1. The actuator is simply a rotating vane inside a fixed slat. The advantage for this is that the slat can be closed, fully open or actively actuated depending on the operating conditions of the airfoil. The effect of rotation direction is investigated both experimentally and numerically and is shown to have an effect.

The actuation frequency is selected according to guidelines from the literature review. There are three dominant frequencies in the flow (i) the shedding frequency from the trailing edge, (ii) the shear instability frequency from the shear layer on the upper surface and (iii) the separation frequency. The actuator is rotated such that the reduced frequency, $f+ = \omega c/U_i nfty$, corresponds to the frequency of one of the dominant modes. Here,$\omega$ corresponds to the actuation frequency, c is the airfoil chord and $U_\infty$ is the free stream velocity. From literature the suggested optimum value for f+ is between 1-2 [4]. The testing was performed for a flow Reynolds number of 50,000 based on the chord and this

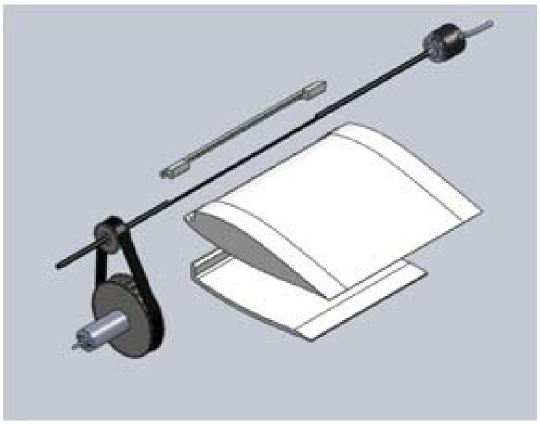


Fig. 2 CAD design for active slat model airfoil

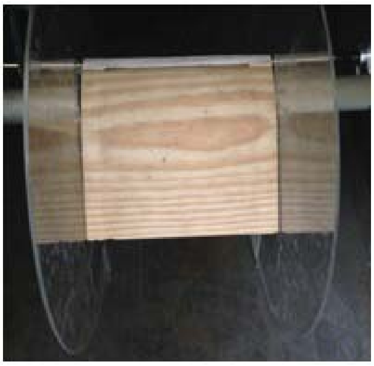


Fig. 3 Assembly of manufactured model showing two splitter blades the active slat and upper surface of the airfoil

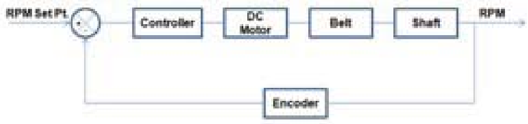



Fig. 4 Controller feedback loop

TABLE I
COORDINATES $x/c$ OF PRESSURE MEASUREMENTS

| Upper | Lower |
| --- | --- |
| 0.16 | 0.28 |
| 0.24 | 0.36 |
| 0.34 | 0.43 |
| 0.42 | 0.49 |
| 0.50 | 0.57 |
| 0.57 | |
| 0.66 | |
| 0.73 | |
| 0.82 | |

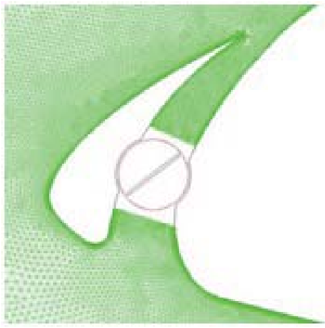


Fig. 5 Close up of mesh. Mesh in inner domain removed for clarity. Red line represents the interface between the rotating and stationary domain

resulted in a rotational speed for the actuator vane of 175-300 RPMs.

### B. Wind Tunnel Model

Fig. 2 shows the CAD design for the airfoil section (upper and lower halves), the actuator rod, the motor drive and encoder. The model was manufactured from wood and assembled in a 0.75x0.75 low turbulence wind tunnel with an open test section. A belt drive system was needed to achieve the required rotational speeds for proper actuation. Two splitter plates were added to the model of width 0.3 m to avoid the tunnel effects as seen from the assembled model in Fig. 3.

### C. Data Acquisition and Control

To ensure that the actuator frequency is properly set, an encoder and feedback mechanism was developed as shown in Fig. 4. An interface program was developed in LabView to control the motor direction and angular speed. The controller sends a digital signal to control the motor direction and a PWM signal to control the motor angular speed. An Omron encoder (E6B2-CWZ6C 1000P/R) returns the rotor rotational speed for feedback and correction. The controller is a PID controller with a sampling period 0.1 second and is implemented using National Instruments PXI system with a multi-function data acquisition card (NI PXI-6225). A total of 14 unsteady pressure measurements were taken (9 on upper surface) using Sensor Technics (LBAS500BF8S) sensors. The measurements were obtained at points documented in Table I.

## III. NUMERICAL MODEL

An unstructured grid was incorporated in a commercial CFD package. Fig. 5 shows a close up of the mesh used in the numerical simulations. The red cylinder represents the interface condition that separates the fixed outer mesh from the rotating core. In most numerical simulations a model is applied for the actuator, in this case a real case scenario is modeled. A prismatic layer is applied on all solid surfaces to improve the boundary layer accuracy. Roughly 250,000 nodes are used in this study and the solutions were checked for grid independence.

The computational domain is shown in Fig. 6. A C-mesh is used that extends 10 chords downstream and 5 chords upstream. Along the outlet, pressure outlet conditions are set and along the inlet, velocity inlet conditions were set.

The solver uses a coupled, unsteady, pressure solver, since the flow is incompressible. Second order discretization was

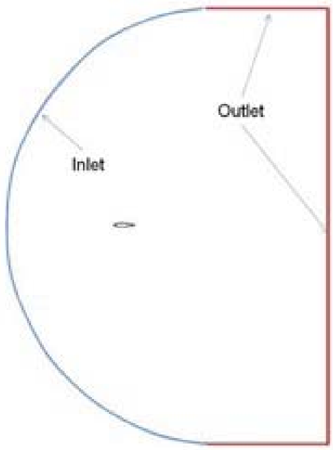



Fig. 6 Computational domain and boundary conditions

used for all convective and diffusive terms. The time step was set at 0.001 seconds and was checked for time independence.

## IV. Results

Fig. 7 compares the pressure and velocity measurements on the upper and lower surface for the airfoil at $\alpha = 0^o$ for the baseline and actuated case. The thick blue and red line represents the data on the upper and lower points for the baseline respectively. The black lines represent the measurement for an actuation of 175 RPM. For this angle of attack it is expected that the actuation will not benefit the aerodynamic performance, and this is clearly seen from the results. The change in the pressure and velocity along the upper surface is minimal.

Fig. 8 compares the pressure and velocity measurements on the upper and lower surface for the airfoil at $\alpha = 15^o$. The black and green lines represent the case for actuation of 175 and 350 RPM respectively. Unlike the case for $\alpha = 0^o$ the slat enhances the mixing on the upper surface and this results in lower pressure (delayed separation) and increased velocity. The effect of the actuation frequency is also apparent. For higher frequency the flow on the upper side has lower pressure and higher velocity an indication that the lift from the airfoil is further increased.

In this flow control technique the effect of direction of rotation is relevant. The actuator can either assist the flow passing through the slat from the pressure side to the suction side, or it can resist it. To experimentally verify this phenomena two measurements were obtained at $\alpha = 10^o$ for valve operating in a favorable clockwise rotation and unfavorable anti-clockwise rotation. Fig. 9 compares the result of this experiment. For favorable actuation the benefit of the active slat is higher than that for unfavorable actuation. It is important to note that in both cases the aerodynamics is improved because the mixing of flow from the slat and stream on the upper surface is achieved.

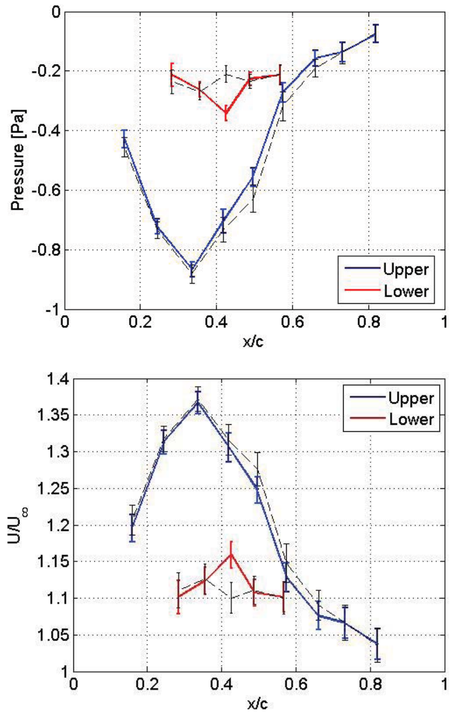



Fig. 7 Pressure and normalized velocity measurements at Re=50,000 and $\alpha = 0^o$. Black lines represent actuated case for a RPM of 175

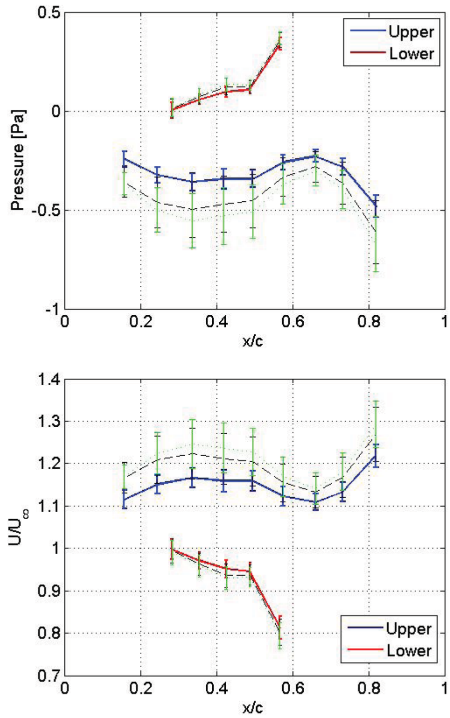



Fig. 8 Pressure and normalized velocity measurements at Re=50,000 and $\alpha = 15^o$. Black lines represent actuated case for a RPM of 175, green lines represent actuated case for a RPM of 350

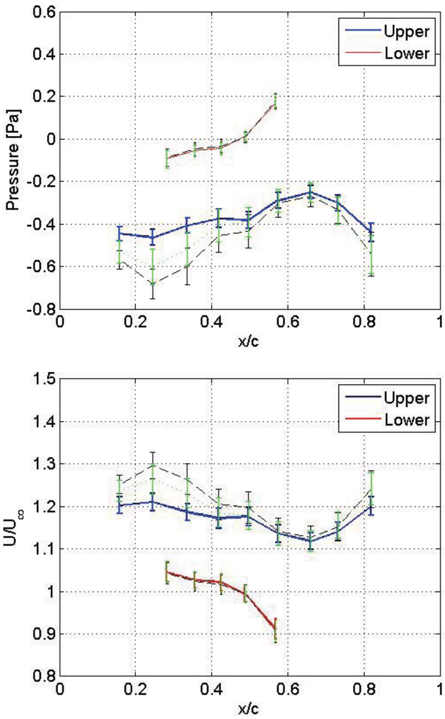



Fig. 9 Pressure and normalized velocity measurements at Re=50,000 and $\alpha = 10^o$. Black lines represent actuated case for a RPM of 175 in clockwise direction, green lines represent actuated case for a RPM of 175 in anti-clockwise direction

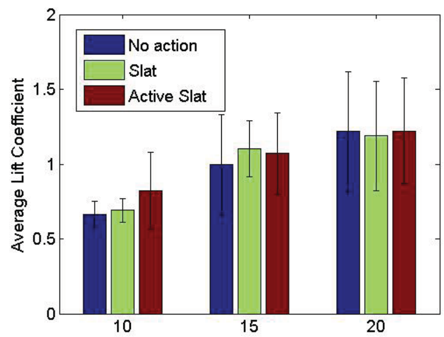
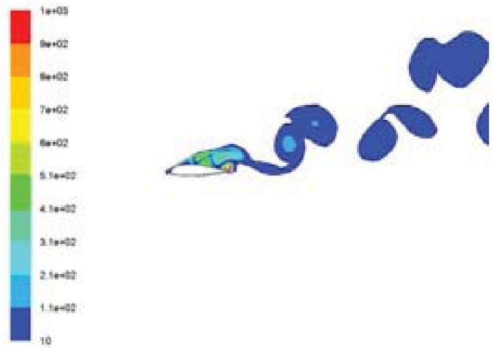
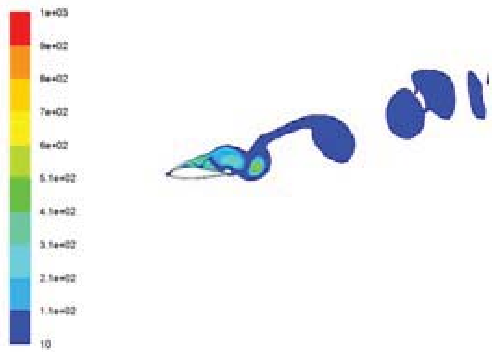



Fig. 10 Numerical results for lift coefficients

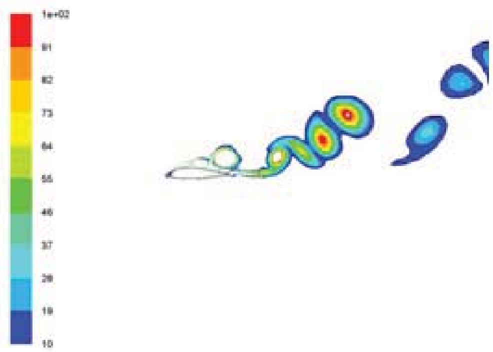
Fig. 10 presents the coefficients of lift obtained from the numerical simulation. In the simulations three cases are considered (i) no slat, (ii) slat without actuation - to mimic fully open case, and (iii) a slat with actuation. From the results it is possible to conclude that the active slat does improve the lift for some angles of attack particularity for $\alpha = 10^o$. The results are not as pronounced as the experimental results and this is caused by two major effects: (i) the wind tunnel is not a laminar tunnel and hence some level of turbulence exists, and (ii) the actuating rotating rod has a different cross section.



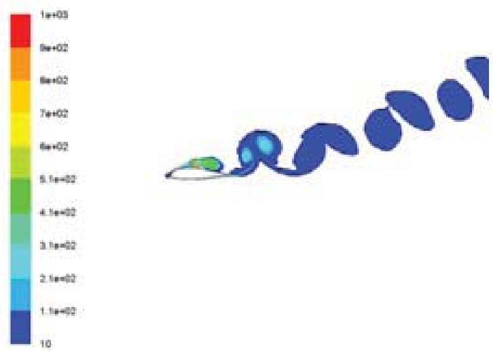
(a) No slat - instantaneous vorticity contours



(b) Slat - instantaneous vorticity contours



(c) Active Control - positive rotation- instantaneous vorticity contours



(d) Active Control - negative rotation- instantaneous vorticity contours

Fig. 11 Numerical modeling of active flow control for a rotating valve

It was not possible to manufacture a rod that was thin enough as that simulated, and hence a half-cylindrical rod was used in the experiment. This turned out to be more beneficial in reality.

Fig. 11 compares the instantaneous vorticity contours for four different simulations (no slat, slat, active slat with favorable actuation, active slat with unfavorable actuation). The flow within the slat is highly complex, and the direction of rotation affects the magnitude and direction of the flow exiting the slat and interacting with the flow on the upper surface of the airfoil and hence can result in higher mixing. The increased mixing delays separation and improves the aerodynamic efficiency of the airfoil.

## V. Conclusion

In summary it is possible to conclude from the experiment that:

1) Using the slat causes the flow to accelerate rapidly after the slat. The increased mixing improves the aerodynamic performance of the airfoil.
2) In an operational sense, the actuator would be placed in the ”closed” position for small angles of attack and hence the airfoil is ”smart”.
3) As seen from the experimental data and numerical simulations the effect of rotation direction is very important. Favorable actuation leads to improved aerodynamic performance.

In the future it is recommended to:

1) Further investigation for different reduced frequencies and slat locations is necessary to determine optimum actuation frequency.
2) Further numerical and experimental studies will be performed to determine effectiveness for higher Reynolds number flows.
3) Spectral data from hotwires will be measured in the wake to determine the efficiency of the actuation. Correlations between the unsteady pressure measurements and the hotwires will be also computed to determine if it is possible to find a relationship between the pressure measurements and the vorticity transported by the mixing flow. This is needed for a future closed loop feedback experiment.
4) Future measurement of unsteady lift and drag for actuated airfoil.

## Acknowledgment

This research was funded by the Science and Technology Development Fund (STDF) project ID 2406.The authors would like to thank the STDF and Cairo University for their support.

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