A Numerical RANS-Based Model of a Nanosecond Pulsed Plasma Actuator for Flow Control over an Airfoil

Roozbeh Aslani†,∗ and Michael Krieger†,∗∗

† Institute of Fluid Mechanics and Heat Transfer - Johannes Kepler University - Linz / Austria

Airfoil stall influences the performance of flight vehicles and remains a challenge for the design of modern aircraft. A Dielectric Barrier Discharge (DBD) device seems to be a promising tool to control the flow over various parts of an aircraft and to suppress separation. A phenomenological model based on dynamic similarity is developed to simulate the control effect of a Nanosecond Dielectric Barrier Discharge (NS-DBD) actuator. A two-dimensional numerical simulation considers the response of the flow past a NACA 0015 airfoil at 14° post stall angle of attack and a Reynolds number of 250,000 to pulsed surface heating at the leading edge. The RANS-based numerical results have been obtained for a baseline simulation (no actuation) and an open-loop control simulation of the airfoil. A one-equation local correlation-based transition model is implemented to capture laminar-turbulent transition. The numerical results of both the baseline and the actuated case are in good agreement with experiments performed by other authors.

© 2019 The Authors Proceedings in Applied Mathematics & Mechanics published by Wiley-VCH Verlag GmbH & Co. KGaA Weinheim

1 Introduction

The field of air flow control has been extended by Dielectric Barrier Discharge (DBD) Plasma Actuators, which appear to be a useful and novel tool for controlling the flow around various aerodynamic bodies. The type of input electrical voltage characterizes the operational condition of plasma actuators. AC-driven actuators (AC-DBD) are the most commonly used. The control authority originates from an electrodynamic effect by imposing a body force on the adjacent flow layer. The flow response due to the momentum deposition is studied extensively by many authors and is still a current research topic.

Applying a repetitive nanosecond pulse to a DBD device generates thermal perturbation in the flow, in contrast to the body forces generated by sinusoidal actuation. This makes a NS-DBD device fundamentally different from other types of actuators. Having an extremely short high-voltage pulse leads to gas discharge in the gap between the electrodes. The net effect of this very complex phenomenon is a thermal energy deposition which consequently raises the temperature in the near-surface gas layer.

The main application of NS-DBD actuators is controlling flow separation. Several observations from experiments[1–3] demonstrate the capability of the leading edge mounted actuators to suppress flow separation. However, the underlying control mechanism is not well understood. A reasonable approach is thus to develop a computational model in order to deepen the understanding of the flow phenomena involved in this actuation method.

2 Computational Modeling

2.1 Governing Equations and Numerical Simulations

The deposited energy into the discharge area of the actuator is directly related to the generated heat and subsequent pressure wave. Thus, in addition to the Navier-Stokes equations, the energy equation, must also be considered.

Two-dimensional numerical simulations are carried out to reproduce the results of the experimental study of Rethmel[1] et al. The model used in the experiment is a NACA 0015 airfoil with a chord length of 0.2032 m and a span of 0.61 m. The comparison is considered for a post-stall angle of attack of 14° at a chord-based Reynolds number of 250,000. The simulations are performed in OpenFOAM, and the SST-κω-SAS-turbulence model is used. A one-equation local correlation-based transition model[4] is implemented to capture laminar-turbulent transition. The actuator is considered as a uniform pulsed heat flux at the surface. Due to the high temperature variation caused by actuation, the perfect gas relationship is used, and the Sutherland relation is considered to model the viscosity change.

2.2 Baseline Results

The time-averaged distributions of pressure coefficients over the chord length are illustrated in Figure 1. The low value of the pressure coefficient at the leading edge (CP,max = 1.03) indicates that a laminar bubble does not exist and that the airfoil is in a deep stall situation. A comparison for the baseline results shows a laminar flow separation at the leading edge, which is in good agreement with experimental results. However, there is a discrepancy concerning the pressure distribution in the
recirculation region near the trailing edge. Such a deviation is a well-known effect of two-dimensional modeling of airfoils with massive separation and is also addressed by other authors [5].

2.3 Actuation Results

Figure 2 shows the time averaged $C_P$ plots of the experimental and numerical simulation results. The numerical simulations are performed for two actuation powers represented by a non-dimensional energy source term $St$. For reasons of comparison, the result obtained from a three-dimensional LES simulation performed by Gaitonde [6] is also provided. The model used by Gaitonde is a semi-empirical actuator model which is calibrated by the strength and speed of the released shock wave from the actuator.

All actuated cases show an improvement over the baseline case. The actuation leads to flow reattachment, and the laminar separation at the leading edge is suppressed. The separation location is moved farther downstream. The lift coefficient increases from $C_L = 0.46$ (baseline) to $C_L = 1.05$ (actuated $St = 116$). The time-averaged pressure distributions of all numerical results show a plateau close the leading edge. The periodic thermal excitation from the actuator induces vortical structures in the shear layer. The generated coherent vortices are responsible for this plateau and have a significant control authority for the flow reattachment.

Figure 2 also shows the numerical results for the increased actuator power. This result confirms the conclusion made by Rethmel that the NS-DBD actuator operates as an active control device and not as a device for passive boundary layer tripping.

3 Conclusions

A phenomenological model, based on dynamic similarity is developed to simulate the control effect of a Nanosecond Dielectric Barrier Discharge (NS-DBD) actuator. The deposited energy per pulse per span is used as an input parameter to calibrate the model. The model can reproduce the relevant physical phenomena observed in experimental setups. The numerical results of the actuated cases are in good agreement with experiments performed by other authors. The generated coherent vortices seem to have the significant control authority to suppress the leading edge separation resulting in flow reattachment.

References

[1] C. Rethmel, J. Little, K. Takashima, A. Sinha, I. V. Adamovich, and M. Samimy, AIAA(January), 1–17 (2011).
[2] I. Popov, Numerical Simulations Of NS-DBD Plasma Actuators For Flow Control, PhD thesis, Delft University of Technology, 2015.
[3] R. Dawson and J. Little, Journal of Applied Physics 113(10) (2013).
[4] F. R. Menter, P. E. Smirnov, T. Liu, and R. Avancha, Flow, Turbulence and Combustion 95(4), 583–619 (2015).
[5] M. Breuer and N. Jovičić, Journal of Turbulence 2, N18 (2001).
[6] D. V. Gaitonde, Computers and Fluids 85, 19–26 (2013).