Direct-forcing immersed boundary modeling of dynamic stall with types of plasma actuator of NACA0012 in turbulent flow

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Abstract

Stall is an aerodynamic phenomenon of an foil which flow separates from the surface and lift drops caused by high angle of attack (AOA). Dynamic stall is another unsteady phenomenon while the foil changes AOA rapidly and the stall delay for a small period. Dielectric barrier discharge (DBD) actuator is a recently popular active flow control device applied on airfoil prevent from stall. Sufficiently high ac electric field can ionize the particle near the plasma region and attract ions move by the electric potential. It can be seen as a body force which force air move toward the airfoil surface. In present research, computational fluid dynamic (CFD) was used for investigating the pitching NACA0012 airfoil with or without DBD actuator flow control at low Reynolds number (2×10^4). Direct-forcing immersed boundary (DFIB) calculates the virtual force by the volume-of-solid (VOS) of mesh, which allows no need to re-generate mesh for complicated fluid-structure interaction (FSI). Applying turbulent model, large eddy simulation (LES), into governing equation can solve the turbulence in present research. Flow field, lift and drag of pitching airfoil with different actuators will be investigated in present research.

Problem description

Dynamic stall is an unsteady and non-linear aero-dynamic phenomenon. This phenomenon is an important limitation of the performance of oscillating foil and also the material structure. Despite the investigation of dynamic stall has been discussed in recent years, the detail of it is still unpredictable.

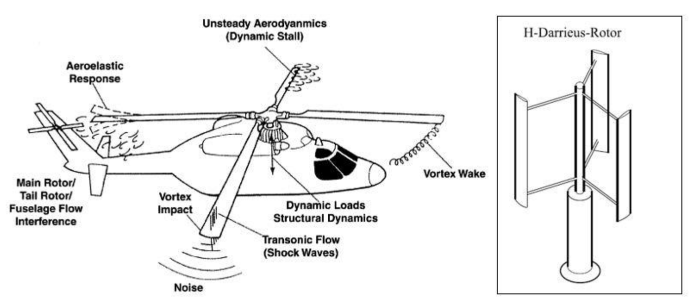

Figure : Dynamic stall was firstly occurs on helicopters.

Oscillating airfoil is the most common device to investigate dynamic stall phenomenon. And dielectric barrier discharge (DBD) plasma actuator is also and popular active flow control device. In this study, cases of oscillating airfoil with types of DBD actuator will be discussed.

Computational domain

This study includes validation of DBD actuator on flow pass a flat plate and cases of dynamic stall. For the DBD validation, velocity profile of ST4 from Shyy et al. [1] is investigated and other domain details are based on [1]. For dynamic stall cases, domain and boundary condition are shown below. NACA0012 airfoil is used for this case.

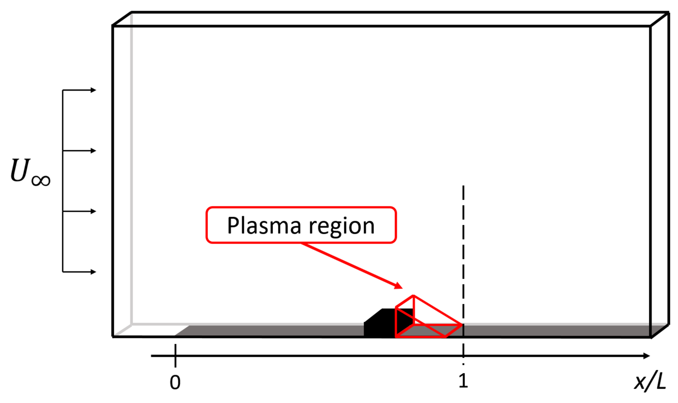

Figure : Domain of DBD actuator model validation.

Boundary	Boundary Condition
Inlet	Uniform flow in
Outlet	Zero-gradient
Lateral	Symmetric
Span-wise	Periodic

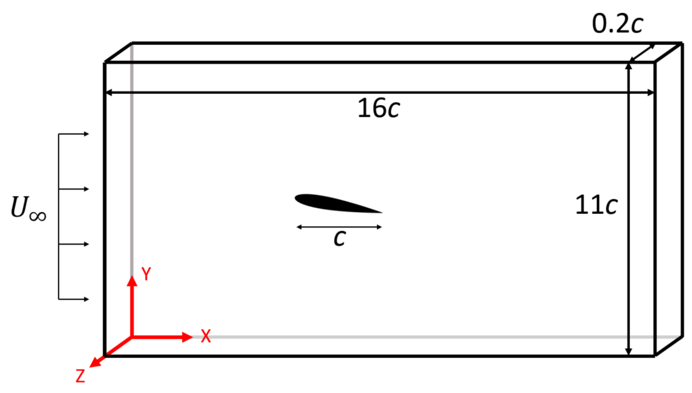

Figure : Boundary condition and domain of airfoil cases.

LES governing equations

The working fluid is assumed to be incompressible and Newtonian. Governing equations include the mass conservation and momentum conservation.

$$\nabla\cdot\mathbf{u}=0$$

$$\frac{\partial\mathbf{u}}{\partial t}+\nabla\cdot(\mathbf{uu})=-\nabla p+\frac{1}{\mathrm{Re}}\nabla^2\mathbf{u}+f$$

The numerical procedures are explained in the following steps.

1. Compute the first intermediate velocity $\mathbf{u}^*$ by just solving the diffusion and convection terms of Navier-Stokes equation.

$$\frac{\mathbf{u}^*-\mathbf{u}^m}{\Delta t}=-\nabla\cdot(\mathbf{uu})+\frac{1}{\mathrm{Re}}\nabla^2\mathbf{u}$$

2. Solve the pressure Poisson equation and then advance to the second intermediate velocity $\mathbf{u}^{**}$.

$$\frac{\mathbf{u}^{**}-\mathbf{u}^*}{\Delta t}=-\nabla p^{m+1}$$

3. Solve for the virtual force f by the VOS(η) of mesh.

$$f=\eta\frac{\mathbf{u}_{solid}^{m+1}-\mathbf{u}^{**}}{\Delta t}$$

4. Solve for the velocity in next time step.

$$\mathbf{u}^{m+1}=\mathbf{u}^{**}+\Delta t\, f$$

Smagorinsky model has been used in this study with Smagorinsky constant, Cs = 0.18, for all of the turbulent flow simulations.

Results and discussion

Model of the body force from DBD actuator is given by [1] as shown in below,

$$F_{tave}=\vartheta\rho_c e_c TE$$

In this DBD actuator validation, the actuator parameters are based on [1]. The solid region of exposed electrode is considered using DFIB method.

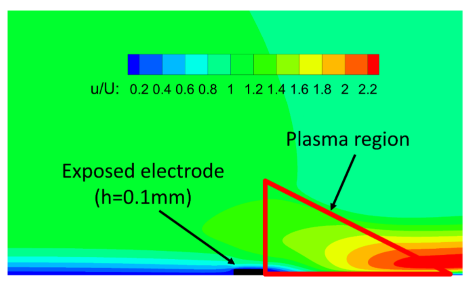

Figure : Illustration of plasma region and the exposed electrode.

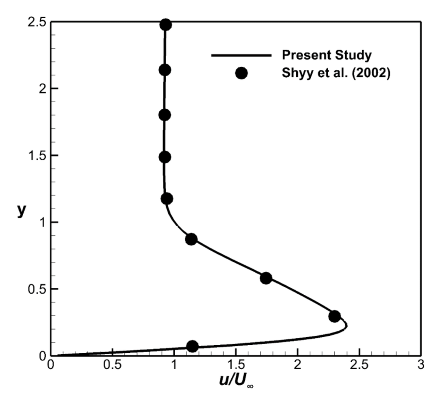

Figure : Velocity profile validation of ST4 with [1].

The DBD actuator is applied on the leading-edge of NACA0012. For the steady actuator cases, DBD actuator parameters are referred from Post et al. [3]. As well as the unsteady DBD actuator setting. The basic idea of unsteady DBD actuator is only active actuator on one-tenth of a unsteady period.

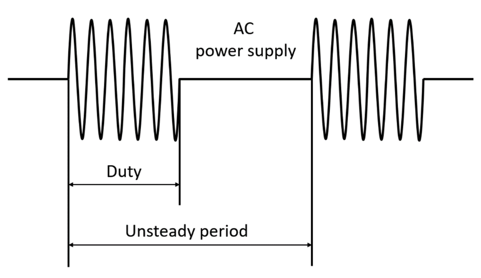

Figure : Illustration of unsteady DBD actuator duty region.

The pivot of the pitching is located at the ¼ chord length from the leading edge.

$$\alpha(t)=\alpha_{mean}+\alpha_{amp}\sin(2\pi f t)$$

Which α_{mean} is the mean AOA, 10°, and α_{amp} is the amplitude AOA, 10°. For airfoils pitching over 15° would be considered as deep dynamic stall. And the reduced frequency, k, is set as 0.4 and defined as,

$$k=\frac{\pi f c}{U_\infty}$$

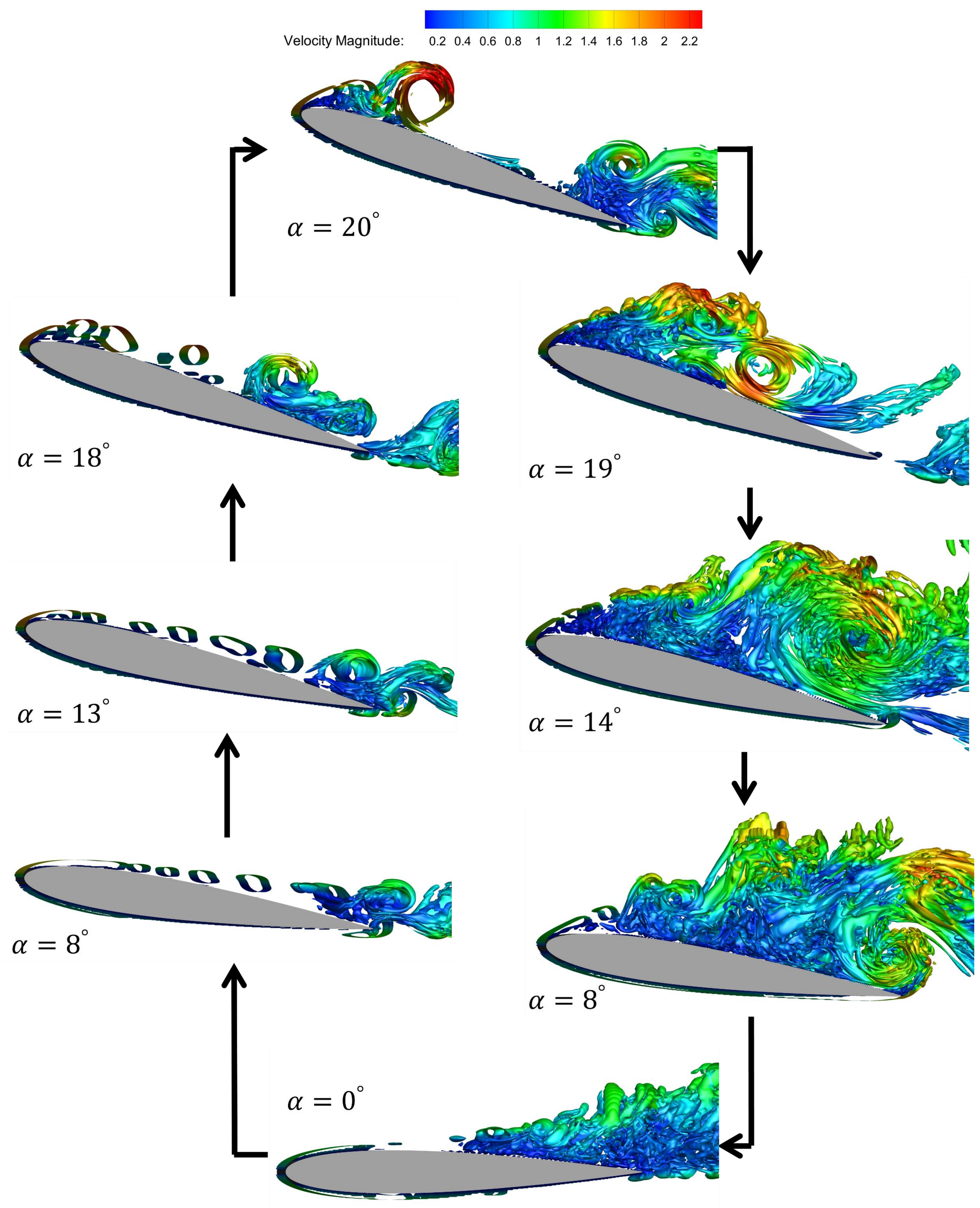

Figure : Iso-surface of Q-criterion 10 and contour by velocity magnitude of oscillating NACA0012 airfoil.

Dynamic stall cases at Re=20,000 are investigated in this study. For case with such high pitching frequency (k=0.4), the leading-edge vortex (LEV) forms from the end of up-stroke to the beginning of down-stroke .The max lift take place at the down-stroke phase around AOA=18°, and detached around AOA=13° in down-stroke which cause a significant lift drops.

Dynamic stall cases at Re=20,000 are investigated in this study. C_D and C_L of present study has much agreement with Guillaud et al. [2].

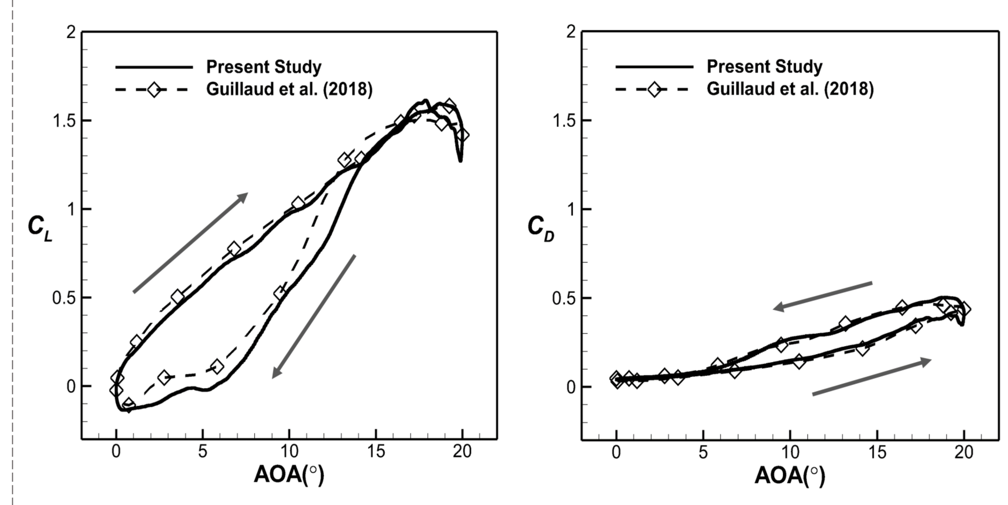

Figure : : C_D and C_L comparison with Guillaud et al. [2].

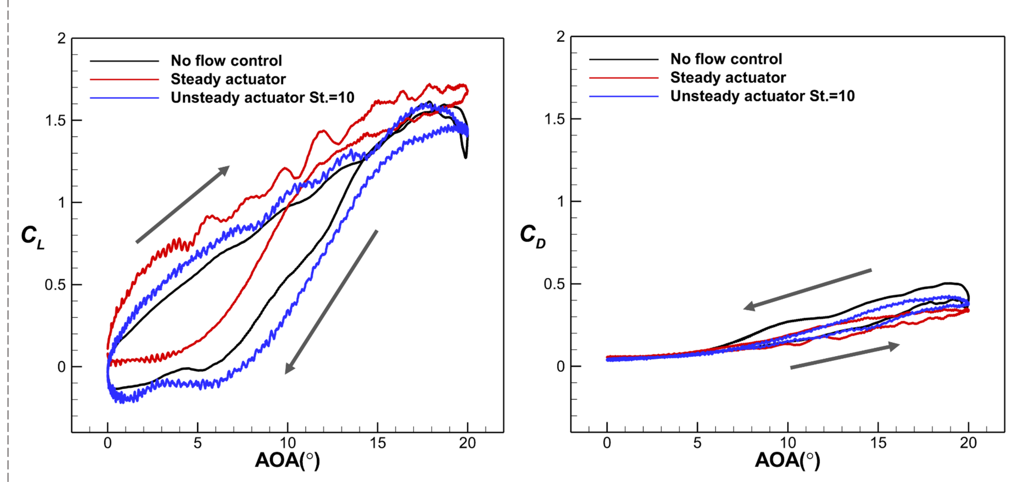

Figure : C_D and C_L of pitching NACA0012 airfoil at Re=20,000 and k=0.4 of no.

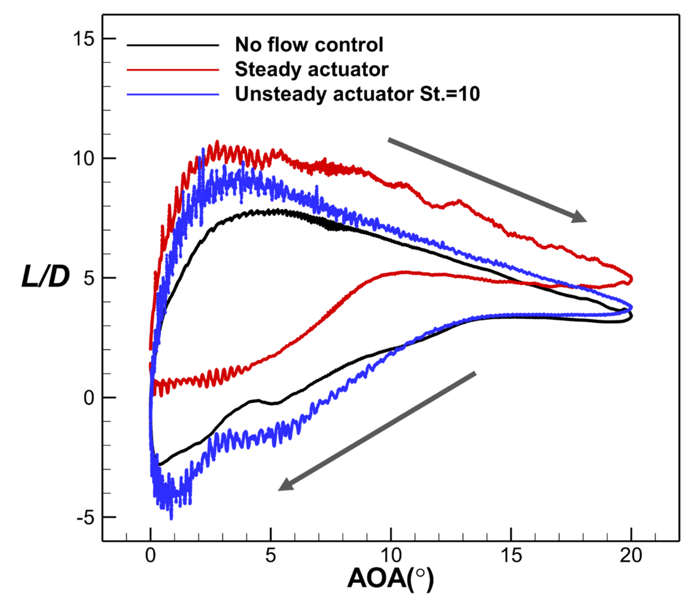

Figure : Lift drag ratio pitching NACA0012 airfoil at Re=20,000 and k=0.4 of no flow control, steady and unsteady actuator.

Conclusions

1. Using DFIB method to model the flow past an oscillating airfoil at low Reynolds number is verified to meet the published result in present study.
2. For reduced frequency, k, is 0.4, the LEV starts to form at very end of up-stroke phase,
3. Steady DBD actuator provides an overall gain in lift expect at the beginning of the down-stroke phase, besides, the overall drag decreases.
4. The effect of unsteady DBD actuator with St.=10 on lift is not significant but the effect on drag is quite similar with steady case.

Acknowledgments

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