Analysis of Co-Flow Jet Effect on Dynamic Stall Characteristics Applying to Rotor Airfoils

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Abstract. The performance of helicopter is limited by the phenomenon of dynamic stall. Dynamic stall is attributed to the time-varying angle of attack (AOA) of blade element resulting from blade flapping cyclic pitch inputs and wake flow. Co-flow jet (CFJ), as a novel flow control technique proposed by the joint research team from University Miami (UM) and AFRL has shown great improvement on lift enhancement, drag reduction due to its strong circulation improvement and turbulent mixing effect. Focusing on dynamic stall characteristics, this paper studies the effect of co-flow jet technique applying to rotor airfoil OA309. Numerical simulations show that CFJ can remove dynamic stall phenomenon occurring on rotor airfoils but the momentum coefficient should be carefully chosen so as to obtain high-efficient control effect.

1. Introduction

The phenomenon of dynamic stall has long been known to be an essential factor that limits helicopter performance [1]. Sources of dynamic stall are very complex. When a helicopter is moving forward, the advancing blade operates at low AOA whereas retreating blade operates at much lower Mach numbers but encounters very high AOA. Besides that, blade elastic deformation, rotor wake and tip vortices also affect the AOA environment of a blade element. The motion of the rotor blade can be simplified as sinusoidal pitching and plunging. The physics of the dynamic stall and related experiments can be seen in references [2-7]. Although Dynamic stall can delay the onset of flow separation, it will bring a rapid aft movement of the center of pressure and dramatic drag increase due to the unstable vortex shedding process. Thus, the dynamic stall of helicopter rotor should be avoided as far as possible.

The novel flow control technique, Co-flow jet, proposed by the joint research team from University of Miami (UM) and AFRL, has shown great improvement on airfoil performance by massive CFD simulations and wind-tunnel experiments [8-12]. Its fundamental configuration is sketched in Figure 1. Near the leading edge on the suction surface of the airfoil, a high energy jet is injected tangentially and the same amount of mass flow is sucked in near the trailing edge. The turbulent shear layer between the main flow and the jet causes a strong turbulence diffusion and mixing which enhance the ability of main flow to overcome the severe adverse pressure gradient and keep flow attached. Moreover, because of the increase of circulation, the lift is also significantly increased. Since Co-flow jet technique poses strong ability of delaying flow separation, it can be predicted that this technique is able to remove the dynamic stall of rotor airfoils.

Focusing on dynamic stall characteristics, the objective of the present work is to validate the viability of Co-flow jet technique using computational fluid dynamic and discuss the control effect of this technique applying to the OA309 airfoil.
2. Overview of CFD method

2.1. Geometry and Mesh
The OA309 airfoil is chosen as baseline to construct CFJ-foil naming CFJ309 for short. Its configuration parameters are shown in Table 1.

| Parameters       | Values    |
|------------------|-----------|
| Injection location | 6%c      |
| Injection size   | 0.75%c    |
| Suction location | 80%c      |
| Suction size     | 1.35%c    |

The computational domain used for CFJ airfoils is shown in Figure 2, in which is clear that it is composed of two subdomains (stationary outer subdomain and rotating inner domain). Between the subdomains there is a sliding interface that allows continuous flux of mass and momentum. Rotating subdomain has a diameter of 3 times chord length while the diameter of stationary outer subdomain is about 50 times chord length.

2.2. Computation set-up
The SST k-ω turbulence model is used to model the turbulent flow characteristics. The spatial and temporal discretization of all equations are specified with a second order scheme to obtain good accuracy in the results. An adaptive time stepping scheme is used with decrease factor 0.86 and increase factor 1.06. The target inner loop is settled as 20 and the maximum inner loop is 40.

The implemented boundary conditions consist of: the velocity inlet on the left side, the pressure outlet on the right side, the sliding interface condition applied between these two domains and no slip walls used for the airfoil and the duct surfaces.

The $y^+$ is set to about one near the walls so as to resolve the turbulent boundary layer. Fixed mass flow rate is allowed to go into duct across the injection boundary. Meanwhile, the suction boundary keeps adjusting static pressure in order to matching the injection mass flow rate.

A sinusoidal pitching motion around the quarter chord point is performed to the rotation domain. The motion expression can be written as:

$$\alpha = \alpha_0 + \alpha_1 \sin(2\pi k \tau)$$  \hspace{1cm} (1)

Where, $\alpha$ is the free stream AOA, $\alpha_0$ is the mean AOA, $\alpha_1$ is the oscillation amplitude of AOA, the reduced frequency $k$ characterizes the degree of unsteadiness of the aerodynamics and $\tau$ is a non-dimensional time variable.
2.3. Validation based on the NACA0012 airfoil

Due to the lacking of experimental data about dynamic stall of OA309 airfoil, the NACA0012 airfoil, whose dynamic stall characteristics has been tested by NASA [2], is selected to validate numerical methods. Table 2 shows the related sinusoidal motion parameters of NACA0012 airfoil. The Mach number is set to 0.301 and the Reynolds number is 3,770,000. The mesh size is about 60,000. Figure 3 presents the numerical and experimental results.

Results show that the numerical lift coefficient agrees well with the experimental lift coefficient, but slightly higher than that when approaching to maximum AOA. Regarding to moment coefficient, as shown in Figure 3, the numerical moment coefficient tends to lower than the experimental moment coefficient when AOA grows bigger, which indicates that numerical simulation over-predicts the dynamic stall effect slightly. The same conclusion can be obtained from the comparison on drag coefficient.

Table 2. Sinusoidal motion parameters of NACA0012 airfoil.

| Parameters | Values |
|------------|--------|
| $\alpha_0$ | 11.48° |
| $\alpha_1$ | 9.84°  |
| $k$        | 0.10   |
3. Study of CFJ effect on dynamic stall

This section studies the performance of CFJ concept on suppressing dynamic stall. Three sinusoidal motion laws are chosen as shown in Table 3. The Mach number is set to 0.3, Reynolds number is 4,000,000 and the mesh size is 60,000. In order to quantify the strength of injection flow related to free stream, the jet momentum coefficient $C_\mu$ is defined in equation (2) (see Reference [12]). When the simulation is implemented, fixed mass flow $m$ is set on injection slot and the $V_{ji}$ is undetermined. For this reason, the nominal jet momentum coefficient is introduced based on $V_{ji}'$ (see equation 2, 3, 4).

$$C_\mu = \frac{m V_{ji}}{0.5 \rho_{\infty} S_{ref}}$$  \hspace{1cm} (2)

$$C_{\mu}' = \frac{m V_{ji}'}{0.5 \rho_{\infty} S_{ref}}$$  \hspace{1cm} (3)

$$V_{ji}' = \frac{m}{\rho_{\infty} S_{ji}}$$  \hspace{1cm} (4)

In equation (4), $S_{ji}$ is the area of injection slot size.

| Table 3. Sinusoidal motion parameters of OA309 and CFJ309 airfoil. |
|------------------|------------------|------------------|------------------|
| Items            | $\alpha_0$      | $\alpha_1$      | $k$              | $C_{\mu}'$      |
| Case1            | 5°               | 10°             | 0.10             | 0.08             |
| Case2            | 10°              | 10°             | 0.10             | 0.08             |
| Case3            | 13°              | 13°             | 0.10             | 0.08             |

3.1. Case 1

Figure 4 shows the force coefficients vary versus AOA under circumstance of case 1 motion law in Table 3. It should be noted that all the force coefficients are consisted of two parts: surface force, injection and suction reacting forces caused by flow injection and suction. In case 1, since the maximum AOA is slightly higher than the static stall AOA, both airfoils still keep flow attached. The lift coefficients of both half-cycles approach each other. Due to unsteady boundary-layer displacement...
thickness effects, the moment coefficients during the upstroke phase doesn’t correspond with those of downstroke. Besides, the moment coefficients of CFJ309 airfoil tend to descend during both upstroke and downstroke motions.

![Diagram](image)

**Figure 4.** Lift, drag and moment coefficient comparison between OA309 and CFJ309 airfoil during case 1 motion

### 3.2. Case 2

As the maximum AOA increases to 20deg in case 2, OA309 airfoil has already been in deep stall status while CFJ309 airfoil remains flow attached, as shown in Figure 5. Vortices contours of upstroke and downstroke motions have shown in Figure 6. Flows around the two airfoils are naturally attached when AOA is 15deg in upstroke motion and no separation appears. When AOA is 20deg, the blowing jet near leading edge forces flow to attach the CFJ309 airfoil surface while separation appears around the OA309 airfoil surface and then propagates downstream quickly. Finally, When AOA is 25deg, flow is fully separated from leading-edge and vortex shedding is observed around the OA309 airfoil.

There exists three layers of vortices near the injection slot of CFJ309 airfoil: (a) clock-wise boundary vortex(blue color) resulted from no-slip wall condition, (b) strong counter-wise CFJ vortex(red color) due to high speed injection effect near leading edge, (c) clock-wise secondary vortex between free stream and injection flow caused by large velocity gradient(blue color). These vortex structures transport the energy of injection flow into free stream so that flow remains attach to the airfoil surface when the maximum AOA is very large, i.e. 20deg.

### 3.3. Case 3

When the maximum AOA is large enough approaching to 13deg, corresponding to case 3 motion law, both of OA309 and CFJ309 airfoil undergo deep stall as we can see in Figure 7. The shapes of force hysteresis loop of CFJ309 airfoil are similar to those of OA309 airfoil except that the hysteresis loop areas of CFJ309 airfoil are smaller which means Co-flow jet can weaken the dynamic stall.

![Diagram](image)

**Figure 5.** Lift, drag and moment coefficient comparison between OA309 and CFJ309 airfoil during case 2 motion
Figure 6. Vortex contours comparison between OA309 and CFJ309 airfoil during case 2 motion

(a) Lift coefficient
(b) Drag coefficient
(c) Moment coefficient

Figure 7. Lift, drag and moment coefficient comparison between OA309 and CFJ309 airfoil during case 3 motion

3.4. Effect of jet momentum coefficient
This part studies how momentum coefficient influences the control of dynamic stall and evaluates efficiency of Co-flow jet technique taking into account the energy consumption of pump (power unit). The pump is used to create high speed jet and suck in equal air at the mean time. Power and efficiency coefficients are defined by equation (5), (6), respectively [12].
\[
P_c = \frac{m C_p T_{in}^{\frac{y-1}{y}}}{\eta}
\]

\[
(L / D) = \frac{CL}{CD + P_c}
\]

The motion law of case 2 in Table 3 is selected and the nominal momentum jet coefficient \( C_{\mu}^* \) ranges from 0.06 to 0.10. In Figure 8, the effect of nominal jet momentum coefficients on force and power coefficients has been demonstrated. The hysteresis loops of lift coefficient are almost overlapped at different jet momentum coefficients and so is for the moment coefficient. The drag coefficient decreases a bit when the jet momentum coefficient increases. Although, force coefficients change little, the power consumption rises quickly with the increase of jet momentum coefficient. Table 4 provides the time average quantities about different configurations. \((L / D)\) of OA309 airfoil is apparently lower than those of CFJ309 airfoil due to deeply dynamic stall. Although larger jet momentum coefficient gives higher lift and lower drag, the power consumption grows that leading to decrease of \((L / D)\). Power consumption should be concerned as selecting an adequate jet momentum coefficient.

**Table 4.** Time average quantities of CFJ309 airfoil at different \( C_{\mu}^* \).

| Items            | \( CL \)   | \( CD \)   | \( P_c \) | \( (L / D) \rangle \) |
|------------------|------------|------------|-----------|-----------------------|
| OA309 airfoil    | 0.9796     | 0.09210    | 0.0000    | 10.6                  |
| \( C_{\mu}^* = 0.06 \) | 1.0941     | 0.01524    | 0.02102   | 30.2                  |
| \( C_{\mu}^* = 0.08 \) | 1.1224     | 0.00951    | 0.03591   | 24.7                  |
| \( C_{\mu}^* = 0.10 \) | 1.1426     | 0.00330    | 0.05394   | 20.0                  |

**Figure 8.** Lift, drag and moment coefficient comparison between OA309 and CFJ309 airfoil at different jet momentum coefficients.
4. Conclusions
In this study, the control effect of Co-flow jet flow technique on dynamic stall are researched. The dynamic stall characteristics of OA309 airfoil are studied at three different types of sinusoidal motion law. Numerical simulations prove that co-flow jet can suppress dynamic stall and prevent massive vortex shedding. Vortex contours show that several vortex layers existing on the suction surface of CFJ309 airfoil contribute to energy mixing and CFJ309 airfoil keep flow attached while OA309 airfoil has been in deep stall. When the maximum AOA is big enough, both of OA309 and CFJ309 airfoil undergo deep stall, but the stall of CFJ309 airfoil can been lessened. The study of jet momentum coefficient shows that the jet momentum coefficient should be carefully chosen so as to obtain high-efficient control effect.

Acknowledgments
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References
[1] Leishman J G 2016 Principles of helicopter aerodynamics (London: Cambridge Univ. Press)
[2] Mccroskey W J et al 1981 The Phenomenon of Dynamic Stall (NASA-TM-81264)
[3] Mccroskey W J et al 1982 An Experimental Study of Dynamic Stall on Advanced Airfoil Sections (NASA-TM-84245-Vol-3)
[4] Choudhry A, Leknys R, Arjomandi M and Kelso R 2014 An insight into the dynamic stall lift characteristics Exp. Therm. & Fluid Sci. 58 188-208
[5] Rival D and Tropea C 2010 Characteristics of pitching and plunging airfoils under dynamic-stall conditions J. of Aircraft 47 80-86
[6] Mulleners K and Markus R 2013 Dynamic stall development Exp. in Fluids 54 1–9
[7] Geissler W and Haselmeyer H 2006 Investigation of dynamic stall onset Aero. Sci. & Tech. 10 590-600
[8] Zha G C and Paxton C D 2006 Novel flow control method for airfoil performance enhancement using co-flow jet Applications of Circulation Control Tech. Progress in Astronautics and Aeronautics 293-314
[9] Wang B Y, Haddoukessouni B, Levy J and Zha G C 2007 Numerical investigations of injection slot size effect on the performance of co-flow jet airfoil 25th AIAA Applied Aerodynamics Conf., Fluid Dynamics and Co-located Conf.
[10] Zha G C and Gao. W 2006 Analysis of jet effects on Co-Flow jet airfoil performance with integrated propulsion system 44th AIAA Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings 2 1273–91
[11] Liu Z X and Zha G C 2016 Transonic airfoil performance enhancement using co-flow jet active flow control 8th AIAA Flow Control Conf. (AIAA 2016-3472)
[12] Lefebvre A M and Zha G C 2014 Co-flow jet airfoil trade study part I: energy consumption and aerodynamic efficiency 32nd AIAA Applied Aerodynamics Conf. (AIAA 2014-2682)