Steady tangential control jet for improving the effectiveness of a rudder under one-engine inoperative condition

P Leelaburanathanakul$^{1,*}$, V Virangkur$^1$, T Wangsiripaisarn$^1$, J Pitakarnnop$^{1,2}$ and A Bunyajitradulya$^{1,3}$

1 Aerospace Engineering, International School of Engineering, Chulalongkorn University, Bangkok, Thailand
2 National Institute of Metrology, Pathum Thani, Thailand
3 Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand

* Corresponding author’s e-mail: phassawat@gmail.com

Abstract. The aim of the research is to numerically investigate the use of a steady tangential control jet (CJ) at the hinge of the vertical stabilizer as an active flow control (AFC) technique to improve the effectiveness of a rudder on a subsonic aircraft during one-engine inoperative (OEI) condition by keeping the flow attached to the control surface. The goals are in two folds: firstly to investigate the effects of CJ parameters, specifically the jet-to-freestream velocity ratio ($r_V$) and the jet slot height ratio ($r_H$), on the vertical stabilizer performance, and secondly to find the optimum CJ condition that yields the improved and optimal performance. In this regard, the optimal condition of the CJ is prescribed as the condition that gives the maximum side force to drag ratio under the requirements that the required minimum trim side force can be achieved and there is an improvement in control surface margin for yawing motion. The investigation is carried out through computational fluid dynamics (CFD) using the Spalart-Allmaras turbulent model. Under the optimal CJ condition, its implementation can provide the required minimum rudder side force coefficient ($C_{y,trim}$) of 1.19 at a rudder drag coefficient ($C_{d}$) of 0.0013, a decrease in drag coefficient of 95% over the baseline case of plain flap without CJ. In addition, there is an improvement in rudder margin with the maximum side force coefficient increase by 42%, and the corresponding drag force coefficient decrease by 25% for the aircraft to yaw in a direction of the still-active engine.

1. Introduction
Rudder is a control surface that is located at the vertical stabilizer of an aircraft and is used for controlling an aircraft’s yaw motion. In an unexpected scenario where one engine experiences a sudden and permanent loss of power (one-engine inoperative condition, OEI), a constant rudder input from the flight crew is required for an aircraft to maintain directional stability. Moreover, additional input from the flight crew in an attempt to yaw the aircraft further in a direction of the still-active engine will further force the rudder to operate at the condition where there is flow separation, lowering the effectiveness of the rudder and significantly increasing the drag when the thrust is already limited and reduced by half from normal operating condition. Most of the extra drag the aircraft suffers when using the rudder to trim is the pressure drag that arises from the flow separation that occurs on the rudder. To find a way to
improve the rudder performance in this situation, the use of a steady tangential control jet, or a steady-
blowing jet, as an active flow control (AFC) technique is investigated in the present study.

In this regard, past studies have shown that the implementation of steady tangential control jet near
the high-deflection flap location of the aircraft wing has proven to be effective in improving the wing’s
lift coefficient, and reducing its drag coefficient by removing local flow separation [1, 2]. Kim et al. [3]
found that the implementation of a steady-blowing jet accommodates the reduction in the shape factor
of the boundary layer, thus lowering the possibility of flow separation. Furthermore, Khodadoust and
Washburn [4] found that the placement of the steady-blowing jet on the flap of a wing shows the most
dramatic improvement in performance when compared to other locations on the main wings. Results from
Melton et al [5] regarding the use of a steady jet on a NACA-0015 airfoil near the hinge of the trailing-
edge flap saw a reduction in the size of the recirculation zone on the suction side of the plain flap over
the baseline case without flow control injection.

With these, the present study aims to improve the performance of a vertical stabilizer during OEI
trim condition after the aircraft has achieved the safe-climb velocity by investigating the use of a steady
tangential control jet (CJ) to reduce flow separation at high rudder deflection angles. Through CFD
 together with the Spalart-Allmaras turbulent model, the flow separation limit and the optimal CJ
condition, including its effectiveness and the improvement in rudder authority, are determined.

In this respect, it should be noted that this is a preliminary design and investigation of the
effectiveness of the use of the CJ in improving the rudder performance during OEI trim by using a
simple 2D simulation of a flapped airfoil. However, it is hoped that the results can be used as a guide
for further detailed design and investigation, with more elaborated simulation and design in order to
account for additional and more realistic configuration and constraints.

2. Design Requirements and Optimization Criteria

Many variables and factors must be considered when attempting to implement flow control techniques
to an aircraft rudder operation in order to obtain the optimum performance of the rudder. In an aircraft
design process, the vertical stabilizer must be designed such that it meets all the directional handling
qualities. One of the main constraints is that the yaw control device must be able to provide sufficient
vertical stabilizer side force to maintain a straight flight path throughout the operational flight envelope
during OEI condition. Estimation of the side force needed for an Airbus A320-200, an example chosen
for this study, yields the required trim side force coefficient

\[ C_{y,\text{trim}} \geq 1.19 \]  

(1)

Another requirement to prove the benefits of the chosen active flow control (AFC) technique is that
once it is activated, the aircraft must have an increased ability to yaw further in the direction of the still-
operating engine. Thus, the rudder deflection angle required to trim the aircraft during OEI condition
must decrease and the maximum available side force coefficient \( C_y \) must increase when the AFC is
activated. Using the dimensions of the aircraft [6] and flight dynamics control derivative, the
requirement on the minimum OEI trim angle is estimated to be

\[ \zeta_{\text{trim}} < 16.8^\circ \text{ (with AFC activated)} \]  

(2)

During OEI, the maximizing of the side force produced and the minimizing of the corresponding
drag caused by trimming are both important in this situation where the available thrust is now limited
and reduced by half from normal operating condition. Hence, the side force to drag ratio must be
maximized. Furthermore, to ensure that the aircraft’s longitudinal stability is not compromised, the cases
that the AFC produces negative drag will not be considered in the optimization process. The optimum
AFC condition will therefore be determined using the following criteria:

\[ \text{Maximum } \frac{C_y}{C_d} \text{ when } C_d > 0 \]  

(3)

Finally, the flow control technique chosen for this study is a steady tangential control jet (CJ) as it is
relatively simple to implement on the vertical tail on an aircraft when compared to other unsteady
alternatives. A reliable pressure supply for the control jet can be taken from the bleed air source provided by an aircraft’s auxiliary power unit (APU) which is already and conveniently located in the same empennage area.

3. Control Jet Design Parameters
The control jet location, slot height, velocity, and direction all play a role in the vertical stabilizer’s performance. To simplify the study, the jet is placed at the hinge of the rudder and is injected tangentially to the rudder’s surface in order to maximize the energizing of low momentum fluid in the near-wall region of the boundary layer. The two chosen design parameters are then the non-dimensionalized jet-to-freestream velocity ratio \( r_V = V_j/V_\infty \) and the slot height ratio \( r_H = H/h \). Here, \( V_j \) is the control jet velocity, \( V_\infty \) is the freestream velocity, \( H \) is the control jet slot height, and \( h \) is the viscous sublayer thickness of the turbulent boundary layer at the hinge point of the rudder. The characteristic viscous sublayer height \( (h) \) is defined at the intersection point between the viscous sublayer velocity profile and the logarithmic velocity profile in the overlap layer, which is estimated by using the coefficients from Coles and Hirst [7] \((\kappa = 0.41, B = 5.0)\). This yields the \( y^+ \) value for the viscous sublayer thickness of 10.80. The jet-to-freestream velocity ratio is varied at 0, 1, 2, 4 while the slot height ratio ranges from 0 (control jet deactivated) to 200.

4. Geometry and CFD Setup
While we use the Airbus A320-200 as an example model, the details of the airfoil geometry used in the vertical stabilizer of the aircraft is not publicly available. We therefore choose an airfoil according to the aircraft design principles for a typical commercial airliner. The model of the 2-D stabilizer is assumed to be a NACA 64A-010 airfoil with a 0.33-chord plain-flap rudder. The rudder is allowed to rotate from 0\(^\circ\) to 25\(^\circ\) according to the limit for an Airbus A320-200 [8] at a typical safe-climb velocity, which is taken to be 81.8 m/s in this study. The dimensions of the control jet slot are shown in Figure 1.

![Figure 1. Detailed view of the control slot design.](image)

A C-mesh computational domain of the size 8 times the vertical stabilizer chord length is prepared. The \( y^+ \) values for the cells nearest to the airfoil wall for all the CFD calculations in our study are meshed structurally to be less than 1, this cell size can accurately resolve the near-wall turbulent boundary layer regions. The simulation is solved using the Reynolds Averaged Navier-Stokes (RANS) approach with the strain/vorticity based Spalart-Allmaras one-equation turbulent model.

![Figure 2. Imposed boundary conditions.](image)

For the simulations, the software package FLUENT\textsuperscript{®} is used. The simulations are performed at sea-level condition, and the specified boundary conditions are summarized in Figure 2. The control jet is
injected tangentially to the rudder’s surface, this is specified in the ‘Jet Inlet’ boundary condition. In the cases where the jet-to-freestream velocity ratio is zero, the ‘Jet Inlet’ boundary condition type is changed to wall. The criteria for the absolute residual threshold for convergence are set to $10^{-6}$ for all quantities to ensure that the solution has reached appropriate convergence.

5. CFD Validation

The validation of the CFD results is divided into 2 parts: the vertical stabilizer drag and the side force. For the drag, comparing with the baseline case that uses a NACA 64A-010 airfoil with an undeflected 0.33-chord plain flap, the drag coefficient data from the baseline setup is consistent with the experimental data by Peterson [9], where the zero-lift drag coefficient of the airfoil at Reynolds number $4.1 \times 10^6$ matches at 0.011.

For the side force, the results from present CFD simulations match the experimental data by Dods [10] with less than 10% difference from rudder deflection angle 0° to 11° as illustrated in Figure 3. After that, from 11° to 17°, the side force coefficients diverge to a maximum difference of 25.6% and then later re-converge to 12.5% difference at the rudder deflection angle of 25°.

\[ \text{Figure 3. Comparison of side force coefficient of a flapped NACA 64A-010 airfoil vs. rudder deflection angle relations between present CFD results (0.33-chord plain flap, Re = 4.1 \times 10^6) and experimental data (0.3-chord plain flap, Re = 4 \times 10^6) by Dods [10].} \]

To further cross-check and validate our simulations under limited experimental data, we seek to compare our simulations with experimental data of similar plain flap airfoil despite some differences in the model and testing conditions as follows. In this regard, only the qualitative trend is of interest.

\[ \text{Figure 4. Comparison of the characteristics of lift coefficient vs. plain flap deflection angle between the present CFD results (0.33-chord plain flap NACA 64A-010, Re = 4.1 \times 10^6) and the experimental data (0.2-chord plain flap W1011, Re = 2 \times 10^5) by Williamson [11].} \]
A study conducted by Williamson [11] on plain flap deflections on an airfoil suggested that the change in lift coefficient (or the side force coefficient) can be broadly classified into three regimes: linear [I], transition [II], and non-linear [III] regimes as indicated in Figure 4. As the flap deflection angle is gradually increased after the linear region [I], the flow on the flap surface starts to separate, resulting in a decreasing or a levelling-off of the lift coefficient, defined as the transition region [II]. The non-linear region [III] indicates that the flow has fully separated from the upper surface [11].

With the above, we compare the relations between lift coefficient and plain flap deflection angle from our CFD simulations with the experimental data of Williamson [11] in Figure 4. While naturally and quantitatively the CFD and the experimental relations show deviation, overall qualitatively they exhibit similar trend.

6. CFD Simulation Results

6.1. Effects of \( r_H \) and \( r_V \) on Side Force Coefficient and Flow Separation Control

To observe the effects of the jet-to-freestream velocity ratio \( r_V \) on the vertical stabilizer performance at a few representative \( r_H \), we look at the effects of \( r_V \) on the side force coefficient \( C_y \) characteristics at two representative \( r_H \) of 3 and 50 in Figure 5. From the figure, the overall increase in the jet-to-freestream velocity ratio \( r_V \) from 0 to 4 can be seen to have more gradual effects on the \( C_y \) characteristic, the increase in \( C_y \), and the flow separation for \( r_H = 3 \) but more abrupt effects for \( r_H = 50 \). In addition, at the same \( r_V \), the increase in \( r_H \) results in the increase in \( C_y \), especially at high rudder deflections. These can be attributed to more momentum being injected into the region of near-wall low momentum fluid in the boundary layer in the case of higher \( r_H \). Furthermore, the results from both cases of \( r_H \) indicate that the CJ can delay flow separation on the suction side of the vertical stabilizer. This can be seen more clearly when we look at the streamline plots for the optimum CJ case of \( r_H = 50 \) in Figure 6 next.

![Figure 5. Effect of the jet-to-freestream velocity ratio \( r_V \) on the side force coefficient and rudder deflection relation on a 0.33-chord plain flap NACA 64A-010 at the slot height ratio \( r_H \) = 3 and 50, Re = 5.6×10^6.](image)

To visualize the effect of \( r_V \) on flow separation control, the streamlines of the cases of various \( r_V \) with \( r_H = 50 \) are shown in Figure 6. It can be observed that \( r_V \) influences the extent of flow separation that occurs near the trailing edge of the stabilizer section. As the control jet is turned on with velocity equals to the freestream velocity (\( r_V = 1 \)), the flow recirculation zone is significantly reduced in size. As \( r_V \) is increased further to 2 and 4, the flow becomes fully attached to the suction surface of the airfoil.

6.2. Control Jet Optimization

To perform control jet design optimization, we compute the side force coefficient \( C_y \) and the drag coefficient \( C_d \) over the domain in which \( r_V \) ranges from 0 (CJ deactivated) to 4, \( r_H \) ranges from 0 to 200, and rudder deflection angle \( \zeta \) ranges from 0 to 25°. Then, we impose the constraints stated in the design requirements (equations 1-3) on the solution domain. To demonstrate the optimization, a surface contour plot of \( C_y/C_d \) as a function of the slot height ratio \( r_H \) and the rudder deflection angle \( \zeta \), at the jet-to-
freestream velocity ratio \( r_V \) of 2 - the value at which we find the optimum point, superimposed by the line of constant \( C_{y,\text{trim}} \) at 1.19 (equation I) is generated and shown in Figure 7.

\[
C_{y}/C_d = \frac{C_{y,\text{trim}}}{1.19} = 1.19 \quad \text{at} \quad r_V = 2 \quad \text{and} \quad \text{Re} = 5.6 \times 10^6.
\]

From Figure 7, it can be seen that for the aircraft to remain directionally trimmed, i.e., the vertical stabilizer providing the side force coefficient of 1.19, a slot height ratio of 50 (H of 4.15 mm on an aircraft) operating at the rudder deflection angle of 14.9° has the maximum side force to drag ratio. The solutions at other velocity ratios, however, do not meet the required AFC design requirements while still keeping the slot dimensions realistic and reasonable to fabricate. Therefore, we find the optimum condition for the CJ to be at the jet-to-freestream velocity ratio \( r_V \) of 2 and the slot height ratio \( r_H \) of 50, which can attain OEI trim at the rudder deflection angle of 14.9°. The streamlines and the velocity contour for this optimum CJ condition at OEI trimming are shown in Figure 8.

In addition to the OEI trim condition, we also investigate the CJ performance at the maximum yaw condition. Hence, we also apply the optimum CJ condition (i.e., \( r_H = 50, r_V = 2 \)) to the rudder deflection angle higher than at OEI trim condition (i.e., \( \zeta = 14.9^\circ \)) in order to find the performance at the maximum yaw condition. As a result, we find the maximum yaw for the case in which CJ is activated at the optimum CJ condition to occur at the maximum rudder deflection angle \( \zeta_{\text{max}} = 25^\circ \). Table 1 summarizes the rudder performance at the optimum CJ condition of \( r_V = 2, r_H = 50 \) for both the trim and the maximum yaw conditions in comparison to the corresponding baseline cases of an unmodified plain-flap rudder.
From Table 1, we can see that when the CJ is used for OEI trimming, at the optimum CJ condition of \( r_H = 50, r_V = 2 \), and a rudder deflection angle \( \zeta = 14.9^\circ \), the rudder has a 95% decrease in drag when compared to the baseline case of 0.33-chord plain-flap rudder without CJ, specifically \( C_d \) decreases from 0.021 to 0.0013. Additionally, using the optimum CJ condition of \( r_H = 50, r_V = 2 \) at the maximum yaw condition (i.e., maximum rudder deflection angle \( \zeta_{\text{max}} = 25^\circ \)) the vertical stabilizer can achieve a side force coefficient of 1.87 at the corresponding drag coefficient of 0.021, a 42% increase in the maximum side force coefficient and a 25% decrease in the corresponding drag coefficient.

**Table 1.** The performance parameters for the baseline, and the modified vertical stabilizer at the optimum CJ condition during OEI trim and maximum yaw conditions

|                          | Baseline Case of Unmodified Plain-Flap Rudder without CJ | Optimized Control Jet \( r_V = 2, r_H = 50 \) |
|--------------------------|---------------------------------------------------------|-------------------------------------------------|
|                          | OEI Trim       | Max Yaw   | OEI Trim       | Max Yaw   |
| \( C_y \)               | 1.19           | 1.32      | 1.19           | 1.87      |
| \( C_d \)               | 0.021          | 0.028     | 0.0013         | 0.021     |
| \( \zeta \)             | 16.8°          | 20°       | 14.9°          | 25°       |

7. Conclusion

This study aims to improve the rudder performance during the one-engine inoperative (OEI) condition by using a steady tangential control jet (CJ) located at the hinge of the rudder deflection as an active flow control (AFC) technique. The optimum CJ condition for the optimum rudder performance is prescribed as the condition at which the rudder has maximum side force to drag ratio at OEI trimming condition while it can also provide additional travel margin. According to the numerical investigation, it was found that the optimum CJ condition for OEI triming to be at the control jet slot height 50 times the height of the viscous sublayer and the jet velocity 2 times the freestream velocity, achieving trim at a rudder deflection angle \( \zeta \) of 14.9°. At this optimum condition, the rudder can provide the necessary \( C_y = 1.19 \) for OEI trimming at a 95% drag reduction when compared to the baseline case of plain-flap rudder without CJ. Additionally, when the CJ is deployed using the optimum condition stated above at the maximum rudder deflection angle \( \zeta_{\text{max}} = 25^\circ \), the rudder still has a 42% increase in maximum side force coefficient and a 25% decrease in the corresponding drag force coefficient when compared to the corresponding baseline case of plain-flap rudder without CJ at max yaw condition. At the optimum CJ condition, the use of a control jet to increase the momentum of low-momentum near-wall fluid on a vertical stabilizer at a high rudder deflection angle completely eliminates flow separation, resulting in lower drag and better overall rudder performance.

8. References

[1] Radespiel R, Burnazzi M, Casper M and Scholz P 2016 Active flow control for high lift with steady blowing The Aeronautical Journal 120 171–200
[2] Kühn T, Ciobaca V, Rudnik R, Gölling B and Breitenstein W 2011 Active flow separation control on a high-lift wing-body configuration part 1: baseline flow and constant blowing 29th AIAA Appl. Aerodynamics Conf. (Honolulu) vol 29 (American Institute of Aeronautics and Astronautics) p 3168
[3] Kim J, Park Y M, Lee J, Kim T, Kim M, Lim J and Jee S 2012 Numerical investigation of jet angle effect on airfoil stall control Appl. Sci. 9 2960
[4] Khodadoust A and Washburn A 2007 Active control of flow separation on a high-lift system with slotted flap at high reynolds number 25th AIAA Appl. Aerodynamics Conf. (Miami) vol 25 (American Institute of Aeronautics and Astronautics) p 4424
[5] Melton L P, Koklu M, Andino M, and Lin J C 2018 Active flow control for trailing edge flap Separation 2018 AIAA Aerospace Sci. Meeting (Kissimmee) p 1799
[6] Airbus S.A.S 2020 A320: aircraft characteristics airport and maintenance planning: 2-2-0 general aircraft dimensions p 3
[7] White F M 1991 Viscous fluid flow 2nd ed. ed L Beamesderfer and J M Morriss (New York: McGraw-Hill, Inc.) pp 411–416
[8] Komite Nasional Keselamatan Transportasi 2014 Aircraft accident investigation report pt. Indonesia air asia airbus a320-216; pk-axc National Transportation Safety Committee p 36
[9] Peterson R F 1950 The boundary-layer and stalling characteristics of the NACA 64A010 airfoil section NACA Ames Aeronautical Laboratory Technical Note p 11
[10] Dods J B 1948 Wind-tunnel investigation of horizontal tails iv: unswept plan form of aspect ratio 2 and a two-dimensional model NACA Ames Aeronautical Laboratory Research Memorandum p 37
[11] Williamson G A 2012 Experimental wind tunnel study of airfoils with large flap deflections at low reynolds numbers University of Illinois at Urbana-Champaign pp 54-5

Acknowledgments
We are grateful and acknowledge helpful discussions and suggestions from Asst. Prof. Niphon Wansophark and Lect. Pinunta Rojratsirikul. P Leelaburanathanakul would like to thank Assoc. Prof. Lucien Baldas and Asst. Prof. Ahmad Batikh at the Institut Clément Ader for their guidance that inspired this project. Finally, the fund provided by the International School of Engineering, Faculty of Engineering, Chulalongkorn University is acknowledged.