Numerical study on technical and conceptual improvements to a civil aircraft trailing-edge flap using passive/active flow control

Gang Wang and Binqian Zhang
School of Aeronautics, Northwestern Polytechnical University, Xi’an, People’s Republic of China

ABSTRACT
Future civil aircrafts require simple, low-noise, and highly efficient trailing-edge flaps. In this study, a detailed numerical study for flap improvements using steady and unsteady Reynolds-averaged Navier–Stokes computations was conducted. A movable trailing edge (MTE) was applied to the main element as a passive flow control method to improve the traditional Fowler flap. A new concept of a backward seamless flap (BSLF) based on the MTE configuration is proposed, which can eliminate external fairings, simplify the mechanisms, and reduce the cruise drag. Then, a wall jet active flow control method was used to improve the BSLF. The improvement effect, flow mechanism, and parameter influences were investigated in detail. The results indicated that the MTE can increase the lift coefficient in the linear segment by 1.2–1.4 for an aerofoil and 0.79 for a wing by controlling the slot flow, energy distribution, and circulation. Moreover, the BSLF provided an improvement in performance higher than 27% over the plain flap, and the wall jet controlled BSLF configuration could reach or even exceed the MTE configuration in terms of performance. The zero-mass jet had a higher control effect and efficiency than the continuous jet. This study highlighted the significance and engineering value for technical improvement and concept exploration of new-generation high-lift devices.

Nomenclature

Abbreviations
AFC Active flow control
BSLF Backward seamless flap
CFD Computational fluid dynamics
MTE Movable trailing edge
P Position
RANS Reynolds-averaged Navier–Stokes
SST Shear stress transport
URANS Unsteady Reynolds-averaged Navier–Stokes
2D Two-dimensional
3D Three-dimensional

Symbols

c Chord (m)
cflap Chord of the flap (m)
clocal Chord of the clean aerofoil (m)
CL Lift coefficient (-)
CLmax Maximum lift coefficient (-)
Cp Pressure coefficient (-)
(-Cp)max Maximum negative Cp (-)
Cμ Momentum coefficient (-)
d Depth of the wall jet slot (m)
f Frequency (Hz)
h Height to surface (m)
H Altitude (km)
i Time-step numbers per actuation cycle (n)
L Lift (N)
L′ Sectional lift (N/m)
im Mass flow rate (kg/s)
M Mach number (-)
p Pressure (Pa)
pt Total pressure (Pa)
P Power (kW)
PCL Power for unit CL increment (kW)
PR Ratio of local to reference pt (-)
Re Reynolds number (-)
Re0 Reynolds number per unit length (-)
t Time (s)
tcontrolon Wall jet opening moment (s)
T Period (s)
v Velocity (m/s)
vT Tangential velocity (m/s)
w Width of the wall jet slot (m)
W Mechanical work (J)

CONTACT Binqian Zhang bqzhang@nwpu.edu.cn
© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
1. Introduction

The high-lift system determines the takeoff and landing performance of an aircraft and significantly affects its safety, comfort, and environmental friendliness (Wang et al., 2008; Wei et al., 2020). The trailing-edge flap is used to generate the extra lift, and Fowler flaps have been widely used in mainstream civil aircraft because of their good lift increment and reliability. However, the traditional Fowler flap has the following shortcomings:

1. The massive flow separation on the flap at large deflections limits the lift performance (Aley et al., 2020; Chu et al., 2012), and the Fowler flap has no effective technical measures to eliminate separation;
2. Positions of the flap side edge and external fairing, as well as flow phenomena such as separation vortexes and boundary layer mixing of the main element and flap, are sources of airframe noise (Ma et al., 2020; Zhang, 2010);
3. Retraction/extension mechanisms of the Fowler flap increase both the operating empty weight and cruise excrescence drag. Studies have shown that removing external fairings can reduce the overall cruise drag by up to 3.3 counts (1 count = 0.0001), resulting in fuel savings of 2.25% (Hartwich et al., 2014, 2017).

Passive and active flow control technologies are potential strategies to solve the above problems, meeting the requirements of a high-efficiency, simple, and low-noise design for new-generation civil aircraft high-lift devices (Jimenez et al., 2011). Moreover, high-lift devices (Aley et al., 2020; Chu et al., 2012; Hartwich et al., 2014; Steinfurth & Haucke, 2018) are also one of the most promising applications for flow control technology.

In recent years, research on the use of flow control techniques and new concepts to improve trailing-edge flaps has been conducted. First, to improve the efficiency of the Fowler flap and restrain the flow separation, several technologies have been proposed and studied. Small and exquisite micro vortex generators can weaken flap separation, but the additional drag cannot be neglected (Chu et al., 2012). The experimental study by Steinfurth and Haucke (2018) has fully proved that the wall jet active flow control (AFC) method can eliminate the separation. However, considering the weight and energy costs, it needs to be in a simplified high-lift system to achieve its comprehensive effect. Plasma actuators can induce a low-pressure region on the upper wing to increase lift (Wei et al., 2020), but the high energy requirement and drag penalty still require further research. A movable trailing edge (MTE) on the main element, as a passive flow control method, has attracted considerable attention and has been applied to new long-range aircrafts because it can improve the flap efficiency without adding new components (Liu et al., 2019; Strüber, 2014; Wang et al., 2011, 2016). In an early research by Wang et al. (2011), the primary lift enhancement effect of MTE was reported, but it was limited by the baseline aerofoil slot width. The MTE deflection was slight, and this effect was not apparent. Wang et al. (2016) studied the MTE control effect on a small deflection flap without separation, but obtained a better lift enhancement effect of the flap deflection increase. Therefore, a larger deflection flap should be further studied to confirm the effect and application scenarios of the MTE. Liu et al. (2019) performed an aerodynamics/mechanism coupling optimization on an MTE aerofoil, verified the effect of MTE, and provided a design strategy closer to practical applications. However, they did not analyse the flow mechanisms. From the above, the potential of MTE has been confirmed, but further research is still needed, focusing on the action mechanisms, design principles, and three-dimensional (3D) spanwise effect.

In addition, to reduce the trailing-edge noise, researchers have proposed trailing-edge brush (Finez et al., 2010), continuous mould line links on the side edge (Streett et al., 2006), seamless variable camber flaps (Urnes & Nguyen, 2013), and other techniques. Currently, most studies are based on model-scale wind tunnel tests or acoustic calculations. However, the effect and feasibility of these new techniques generally need to be verified and confirmed through large-scale wind tunnel or flight tests (Dobrzynski, 2010; Zhang, 2010).
Furthermore, several flap designs for simplifying the drive mechanisms have been studied. The simple hinge flap has the simplest structure. However, flow separation easily occurs when the deflection is slightly larger, resulting in a lift loss and drag increase. This separation can be compensated by the AFC system (Hartwich et al., 2014). However, because the separation area often occupies the entire upper surface of the flap, the energy requirement of the AFC system for a simple hinge flap is high, which partially offsets its weight reduction benefits. The multi-hinge variable camber flap improves the simple hinge flap, and can theoretically achieve smooth camber changes (Urnes & Nguyen, 2013). However, the multi-hinges increase the structural weight and mechanism complexity. This concept can adaptively change the camber to improve the cruise economy, but its performance as a high-lift device is poor, and the disclosed design also retains the inboard Fowler flap to ensure sufficient lift (Nguyen et al., 2015). These simplified flaps have apparent benefits for the weight and cruise drag, but the lift loss requires additional weight and power requirements of the AFC system (Hartwich et al., 2014; Melton et al., 2019; Vatsa et al., 2018). Although Cai et al. (2018) showed that an AFC-enabled aircraft with simple hinge flaps has economic advantages in most tasks, it is still necessary to explore new concepts for flaps with a better initial lift enhancement ability that is beneficial for streamlining the AFC system. In addition, Hartwich et al. (2014, 2016) indicated that although the effect of the AFC method has been widely recognized, the actuator layout, working mode, and mass flow requirements still need to be carefully studied for specific designs.

In summary, although technical and conceptual improvements for flaps have continuously progressed, in-depth mechanistic research and new concepts with a small lift loss are still needed. Therefore, in this study, issue 1) listed at the beginning of the introduction is addressed, and the MTE method is applied to improve flap efficiency. Then, in response to issue 3), the concept of a backward seamless flap (BSLF) based on the MTE aerofoil is proposed, and the AFC method is applied to improve the lift performance. Numerical studies of two-dimensional (2D) aerofoils and 3D wings were conducted to determine the real effects of the technical and conceptual improvements studied. For the MTE study, this study mainly focused on the design principles, control mechanisms, and control effect on a 3D wing. Some conclusions that can promote practical applications are provided. For the BSLF study, the performance advantages of this new design over plain flaps are indicated, the design issues of the wall jet controlled BSLF configuration are quantitatively studied, and suggestions and insights on the wall jet arrangement, momentum coefficient, and actuation mode are provided. Overall, this study provides references and new ideas for flap improvements.

The remainder of this paper is organized as follows. Section 2 introduces the numerical method and the basic research models. Sections 3–5 systematically investigate the MTE, BSLF, and AFC-enabled BSLF aerofoils and wings, respectively. The performance advantages, control mechanisms, design principles, parameter influence analysis, and 3D spanwise effects are presented. Section 6 concludes the paper with some concluding remarks.

2. Numerical method and baseline aerofoils

2.1. Numerical method and verification

The 30P30N multi-element aerofoil was used as the standard model for verification. The computational conditions were the same as those in previous experiments (Chin et al., 1993), that is, \( M = 0.20, Re = 9.0 \times 10^6 \), and the range of the angle of attack was 4°–24°.

Numerical simulations were conducted by solving the Reynolds-averaged Navier–Stokes (RANS) equations using the finite volume method, which adopts the implicit solver method. The diffusion and convective terms in the governing equations were addressed by adopting the central difference and second-order upwind difference scheme, respectively. The implicit second-order backward Euler scheme was used for the time discretization. The multi-grid technique was used to accelerate the convergence and improve the computational efficiency.

The turbulence viscosity terms of the RANS equations were specified by the shear stress transport (SST) \( k-\omega \) turbulence model because of its better performance in capturing the separation of high-lift systems (Rumsey & Ying, 2002). For the high angle of attack cases with vortex-separated flow, the unsteady effect was reduced or eliminated by appropriately adjusting the timescale.

Multi-block O-H structured grids (Yu et al., 2020) were generated before the simulations, as shown in Figure 1. To capture the boundary layer flow details, an O-grid surrounding the model was used to ensure grid orthogonality near the surface, and the remaining computational domains were the H-grid. The dimensionless wall-normal distance \( y^+ \) of the first grid over the wall was approximately 1.0, and the stretching ratio of the boundary layer grid in the normal-wall direction was less than 1.05. In addition, the points near the critical regions were refined to improve the simulation accuracy. A grid convergence study was conducted at \( \alpha = 8^\circ \), and Figure 2 displays the results. As the number of grids increased, \( C_L \) and \( C_D \) tended to converge, and a medium number of grids was selected for the simulation.
Figures 3 and 4 show comparisons of the lift coefficients, velocity profiles, and pressure distributions obtained in the wind tunnel tests (Chin et al., 1993; Kim et al., 2002) and computational fluid dynamics (CFD) results. It can be confirmed that the CFD method adopted in this study can effectively predict the aerodynamic characteristics of high-lift aerofoil. The velocity profiles revealed some differences in the slat wake regions, which may be related to the turbulence model, transition, 3D, or possibly unsteady effects (Rumsey et al., 1998).

2.2. Baseline aerofoils

The baseline aerofoils in this study were two typical three-element aerofoils for a landing-state civil aircraft, which is a new type of subsonic civil aircraft in the process of design and research. Its flight Mach number is 0.83, and its size is similar to that of B777. Figure 5 shows the wing before the engine installation. The two aerofoils include a slat and a Fowler flap with a 40° deflection, which are usually deployed on the inner and outer wings. They were named Sections A and B. Figure 5 also shows their position and shape; the relative flap thickness of Section A is higher than that of Section B. The study of these two representative aerofoils can reveal the general effects and universal flow mechanisms in most cases.

Figure 6 shows the calculated lift characteristics under the conditions of $M = 0.2$, $H = 0\,\text{km}$, and $Re_0 = 4.66 \times 10^6$. The $C_L$ of these two baseline aerofoils in the design state ($\alpha = 10^\circ$) was only approximately 2.50, which makes it difficult to meet the design requirements. In comparison, the $C_L$ of the 30P30N aerofoil in a similar state was approximately 3.50. The baseline $C_{L_{max}}$ values were also low (less than 3.0).

Figure 7 depicts the flow field near the flaps at $\alpha = 10^\circ$. As shown in the figures, there was a massive separation on each flap, accounting for 70%–80% of the entire flap chord, resulting in no apparent downward deflection of the upper surface flow. The separation range of Baseline A was slightly smaller than that of Baseline B because of the larger leading-edge radius and relative thickness of the flap, which has a stronger anti-separation ability. This separation is the main reason for the unsatisfactory aerodynamic performance of the baseline aerofoils.

3. Technical improvement: a movable trailing edge for the main element

Separation control is the key to improving the aerodynamic performance of a multi-element aerofoil. Therefore, the MTE method was selected for technical improvement of the baseline aerofoil, as this method has the potential to address the flap failure issue.

3.1. MTE deflection design

The MTE method was applied to the main element, as shown in Figure 8, while the position and deflection of the flap were maintained constant. The MTE is driven by a single hinge mechanism, and its deflection $\delta_{MT}$ is defined as the angle difference between the MTE and the baseline. In practice, $\delta_{MT}$ can be measured by the rotation angle of the hinge shaft, as shown in Figure 9.

The lift coefficient increment $\Delta C_L$ at $\alpha = 10^\circ$ was used as the design index for $\delta_{MT}$. The results in Figure 10 indicate that the MTE can effectively improve the lift of the baseline aerofoils. The best lift enhancement effect was obtained with tangential deflection, that is, the state where the extended line of the MTE was tangential to the upper surface of the flap, as shown in Figure 10(a) and (b). This conclusion provides a guide for the MTE deflection design, and the tangential deflection will be used for subsequent investigations.

Figure 11 shows the lift and drag characteristics of the MTE aerofoils. The linear-segment $C_L$ values were significantly improved by 1.240 and 1.400, respectively, and $C_{L_{max}}$ also increased by approximately 0.450. Because the
Figure 3. Comparison of lift coefficients and velocity profiles at $\alpha = 8^\circ$ obtained in the wind tunnel tests and CFD results.

Figure 4. Comparison of pressure distributions obtained in the wind tunnel tests and CFD results.
MTE method mainly improves flap efficiency, the stall angle of attack of the MTE aerofoils was reduced (Andersen, 2010). The reason for the reduction in the stall angle of attack will be analyzed later. Moreover, the MTE can reduce the drag at the same lift.

### 3.2. MTE flow control mechanisms

In the previous section, the MTE deflection design principle was determined and its lift-enhancement effect was confirmed. In this section, the MTE control mechanisms are analyzed to make a more rational use of this technology.

First, the MTE control effect on the flow through the slot was analyzed. Figure 12 shows the Mach number contours and streamline diagrams before and after the use of the MTE when $\alpha = 10^\circ$. The separation of the flaps was eliminated by MTE deflection. Separation is the primary source of aerofoil drag, and flow attachment is the reason for the drag reduction shown in Figure 11. The figures also illustrate the control of the...
MTE in the slot-flow direction. Benefitting from the tangential deflection design, the direction of the slot flow was changed from an approximately horizontal backward flow to approximately tangential to the upper surface. The high-energy slot flow could sweep the upper surface more thoroughly; that is, the sweeping effect was strengthened, which was conducive to blowing off the low-energy flow on the flap and enhancing its anti-separation ability.

The MTE changes the slot flow direction and slot parameters, which may affect the slot-flow strength. Figure 13 explores this possibility. It can be seen from the velocity profiles at a fixed front position on the flap that after the MTE deflection, a local velocity increase appeared in the slot flow, particularly in section B. However, the overall slot flow velocity under the control of the MTE was not higher than that of the baseline. The high-speed flow at the leading edge of the baseline flap is mainly derived from the acceleration effect of the flow around the flap nose. The MTE narrows the slot gap; although this helps to accelerate the flow through the channel, it also suppresses the acceleration effect of the flow around the nose. As a result, the MTE changes the velocity profile of the slot flow but does not enhance its strength.

The separation control ability of the MTE is also applicable at low angles of attack. Figure 14 compares the flow characteristics of Section A with and without MTE at $\alpha = 0^\circ$. It can be observed that the control effect of MTE is still better. This is also why the MTE has a nearly constant $\Delta C_L$ for all small to moderate angles of attack, as shown in Figure 11.

In conclusion, the MTE control effect on the slot flow is a simultaneous change in the direction and local velocity profile. However, the former enhances the sweeping effect, which is the main reason for the elimination of the separation, as the slot flow strength does not change significantly.

Next, the influence of the MTE on the energy distribution of the flow field was studied. Figure 15 shows the total pressure contours of the baseline and MTE aerofoils in Section A (the conclusions are the same for Section B and will not be repeated here). The slot flow of the baseline aerofoil was backward and farther from the upper surface.
surface of the flap. This high-energy flow failed to help the flap boundary layer resist the reverse pressure gradient caused by the large flap deflection, and severe separation occurred. Macroscopically, the characteristics of the flow field showed a low degree of high-energy flow deflection, and the lift enhancement ability was insufficient.

After the MTE deflection, the slot flow in the appropriate direction isolated the main element wake and the flap boundary layer, and this high-energy flow enhanced the ability to withstand the pressure gradient of the flap boundary layer. On the other hand, the boundary layer on the MTE became thicker owing to the downward deflection, thus increasing the width of the main element wake, which forced the slot flow to follow the flap more closely. Macroscopically, this manifests as an increase in the degree of high-energy flow deflection, which improves the high-lift ability.

In summary, the MTE effectively controls the flow field energy distribution, supports the flap boundary layer to withstand the pressure gradient, and causes the high-energy slot flow to sit closely on the flap, which improves the high-lift efficiency in a versatile manner.

Finally, the MTE control effect on the aerofoil circulation is presented. Figure 16 shows a comparison of the pressure distributions before and after MTE deflection. It can be seen that the pressure difference at the trailing edge of the main element increased as the camber increased. At the same time, the constant pressure area of separation on the flap disappeared. Moreover, the peak negative pressure at the flap leading edge was significantly reduced, which reflected the unloading effect of the narrowed slot on the flap. These changes reduce the flap separation risk and produce a more reasonable pressure distribution (Smith, 1975).
Figure 12. Comparison of the flow characteristics of the MTE and baseline aerofoils at $\alpha = 10^\circ$.

Figure 13. Leading-edge velocity profiles of flaps before and after the MTE deflection at $\alpha = 10^\circ$. 
Figure 14. Comparison of flow characteristics of the MTE A and Baseline A at $\alpha = 0^\circ$.

Figure 15. Total pressure contours of Section A before and after the MTE deflection at $\alpha = 10^\circ$, respectively.

Figure 16. Comparison of $C_p$ and $L'$ of the MTE and baseline aerofoils at $\alpha = 10^\circ$. 
To analyse the circulation control effect of the MTE quantitatively, the sectional lift, $L'$, is defined as follows:

$$L' = \int_{c} \Delta p \, dc,$$

where $c$ is the chord length and $\Delta p$ is the pressure difference between the upper and lower surfaces. Using the pressure coefficient $C_p$ to express $\Delta p$, $L'$ can be rewritten as:

$$L' = \frac{1}{2} \rho_{\infty} v_{\infty}^2 \int_{c} \Delta C_p \, dc,$$

where $\rho_{\infty}$ and $v_{\infty}$ are the density and velocity of the free stream, respectively, and $\Delta C_p$ represents the difference in $C_p$ between the upper and lower surfaces.

The $L'$ results in Figure 16 show that the lift increments mainly arise from the main element. On the one hand, the camber increase from the MTE deflection improves the circulation generation ability. On the other hand, the elimination of the separation on the flap enhances the upwash effect on the main element, leading to an induced circulation increase. In addition, the main element with higher lift has an enhanced up-wash effect on the slat, whose circulation increases accordingly. However, even if the separation is eliminated, the flap circulation exhibits little change or even decreases. This is due to the strong unloading effect of the narrowed slot, which suppresses flap circulation. The above analysis shows that the MTE improves flap efficiency by transferring circulation to the main element and slat rather than by increasing the circulation of the flap itself.

The decrease in the stall angle of attack of the MTE aerofoil can now be explained. The MTE enhances the up-wash effect and significantly lowers the pressure on the slat and main element head, which causes the upper surface flow of the MTE aerofoil to withstand a stronger reverse pressure gradient. This makes it more challenging to maintain attachment, thus increasing the risk of stalling. The velocity profiles of the main element shown in Figure 17 present the evidence. In the $\alpha$ range of 10° to 14°, the intense pressure gradient pushed the near-wall velocity of MTE A to reduce, as indicated by the black dots. For Baseline A, the near-wall velocity distribution did not change significantly, as shown by the pink dots.

In conclusion, MTE can produce a more reasonable flap pressure distribution. Moreover, it enlarges the circulation and moves it forward by increasing the camber and enhancing the induction of various elements.

The following conclusions regarding the MTE flow control mechanisms can be drawn from the above analysis.

(1) The MTE controls the slot flow direction, thereby enhancing the sweeping effect and eliminating the separation on the flap;

(2) The MTE controls the energy distribution of the flow field, enhancing the ability of the flap boundary layer to withstand the pressure gradient and causing the high-energy flow to become attached to the flap;

(3) The MTE controls the circulation, causing it to enlarge and move forward by increasing the camber and enhancing the induction of various elements.

From the above analysis, the reasons for the $C_{L}$s of the baseline aerofoils lower than those of the highly optimized multi-element aerofoils such as 30P30N can be determined:

(1) The low-speed performance of a clean supercritical aerofoil is poor, and the upper surface flow is approximately horizontal;
(2) The wide slot reduces the up-wash effect of the flap on the main element;
(3) The severe separation fails the large deflection flap.

Although aerodynamic optimization can further improve the high-lift ability, the contradiction between the high-speed and low-speed performance owing to a clean aerofoil is still difficult to resolve. Therefore, it is necessary to adopt a new flow control technology to promote low-speed performance, such as the MTE, without significantly changing the shape of the aircraft.

The mechanism analysis shows that the control effect of the MTE is multifaceted. Compared with the performance improvement method of merely adjusting the relative position of the flap and main element, the separation elimination effect and aerodynamic performance gains of MTE come from the superposition of multiple favorable effects, including the control of slot flow direction and the optimization of slot geometrical parameters, and the increase in the overall camber of the aerofoil. These correspond to the above causes of the lift defect, which demonstrates that the MTE is an efficient lift enhancement method. Moreover, the high-lift system optimization combined with the MTE can also obtain a larger design space and performance improvement.

The practical application of MTE can consider two aspects. First, it can be designed as a part of the high-lift system in the initial design stage of the flap to expand the design space and improve the takeoff and landing performance. Second, it can also be used as a supplement to the high-lift device to provide sufficient 'lift reserve' for the aircraft when short takeoffs and landings are required or when the takeoff and landing conditions change. Moreover, after the aircraft touches down in the landing phase, the MTE can be used as an upper deflection brake.

3.3. 3D wing study for MTE

To verify the effect of MTE applied to 3D wings, referring to the comparative analysis of the 2D aerofoil and the 3D wing (Ghalandari et al., 2019), a Section A-based wing was designed, as shown in Figure 18. The aerofoils of this 3D model were scaled from Section A (with or without a flap). The wing was divided into three parts: inner high-lift, outer high-lift, and outer wing sections, corresponding to the three typical wing parts of the existing aircraft takeoff and landing configuration. The three parts had the same leading-edge sweep angle, and the outer two parts had a larger trailing-edge sweep angle than the inner part. The junction of the high-lift sections and the outer wing section was addressed using the patched-grid method (Chu et al., 2012) such that the cross-sectional grids of the high-lift parts could be as consistent as possible with the 2D cases. Moreover, the 3D and 2D studies had the same free-flow conditions and MTE deflections, and the grid number of the 3D calculations was approximately 31 million.

Figure 19 shows a performance comparison of the baseline and MTE wings. Consistent with the 2D results, the MTE significantly increased the lift. The linear-segment $C_L$ values improved considerably by 0.790, and $C_{L_{\text{max}}}$ also increased by approximately 0.531. In addition, the MTE could reduce the drag when fixing the $C_L$.

The 3D spanwise effect influences the MTE control effect. Figure 20 shows the surface streamlines and separation regions of the wing with and without MTE. In the figures, $PR$ represents the ratio of the local $P_t$ to the far-field $P_t$, which can characterize low-energy separation. Although the separation area of the MTE wing was significantly reduced, there was still separation on the flap of the outer high-lift section. This was because the trailing edge of this section had a large sweep angle, causing a strong spanwise flow, which weakened the separation control ability of the MTE.

In summary, the MTE on the 3D wing still exhibited a significant lift enhancement. However, the 3D spanwise effect results in difficulties to the separation control ability of MTE and weaken the control effect on a wing part with large trailing-edge sweep angles. Therefore, in practice, the flap deflection at this position can be appropriately reduced to obtain the attached flow.

4. Conceptual improvement: Backward seamless flap

4.1. Description

In the previous section, the MTE method was used to improve the lift performance of the baseline aerofoil in
response to issue 1) mentioned in the Introduction. However, to simplify the Fowler flap and reduce its adverse impact on aircraft, that is, to address issue 3), further research is required.

In this section, the concept of the BSLF is proposed based on the MTE aerofoil. Its purpose is to remove the external mechanisms of the Fowler flap to reduce the empty weight and cruise drag. Moreover, removing the slot also has the potential to reduce takeoff and landing noise. A schematic of this concept is shown in Figure 21. The driving mechanisms of the BSLF are internal and are mainly composed of sliding rails, pushrods, and the MTE. The sliding rails are located on the lower surface of the MTE and on the upper surface of the flap. The spoilers for gust mitigation and drag increase are arranged in front of the MTE. The motion process is as follows: driven
by the pushrods, the BSLF slides out to a specific position along the sliding rails, and the MTE is used to adjust the deflection, as shown in Figure 22. The pushrods provide the driving force and also ensure the overall strength of the entire system.

4.2. Aerodynamic performance

For comparison, the BSLF aerofoils adopted the same flap deflection as the baseline aerofoils and the same MTE deflection as in the previous section. Figure 23 compares the lift and drag characteristics of the BSLF, MTE, and baseline aerofoils. The results show that the BSLF aerofoils had considerably better performance than the baseline aerofoils but incurred a loss of linear-segment $C_L$ of 0.4–0.5 compared with the MTE aerofoils. The drag characteristics of BSLF aerofoils were also between the MTE and baseline aerofoils.

There was a large-scale separation on the BSLF after removing the slot, which directly causes a loss of flap efficiency and reduces lift, as shown in Figure 24. For the BSLF aerofoils, the mixing boundary layers of the main element and the BSLF continue to thicken because they are not partitioned by the slot flow. This low-energy flow region separates quickly under the reverse pressure gradient owing to the geometric camber. For the MTE aerofoils, as analyzed in Section 3.2, the slot flow can effectively prevent the above boundary layer mixing, which makes the boundary layer on the flap thinner and strengthens its anti-separation ability. Therefore, considering that the BSLF cannot use the partition effect of the slot flow, replenishing energy for the low-energy mixing boundary layer becomes a possible method to recover the BSLF aerofoil performance.

4.3. Comparison of the BSLF and plain flap

At present, most seamless trailing-edge high-lift devices are plain flaps, which can also realize the theoretical cruise drag and noise benefits by eliminating external fairings and gaps. However, the BSLF concept is superior to plain flaps in terms of basic high-lift ability. In this section, this superiority is demonstrated.

A plain flap aerofoil (Plain A) was designed for comparison with BSLF A; the flap chord and deflection of Plain A were equal to those of BSLF A. Figure 25 shows a comparison of the lift and drag characteristics. The BSLF exhibited a significantly better performance than the plain flap. The difference in $C_L$ between them was more than 0.6 at $\alpha = 10^\circ$, which corresponds to a 27.7% performance advantage. This is sufficient for BSLF to be preferred in engineering applications. The drag characteristics of BSLF aerofoils were also advantageous.

The more extended aerofoil chord provided by a backward flap results in a larger wing area, which is one of the reasons for the superior lift of the BSLF. Figure 26 shows a comparison of the pressure distributions at $\alpha = 10^\circ$. As shown, because the MTE of the main element was deflected downward in advance, the equivalent deflection of the BSLF was smaller than that of the plain flap, resulting in a gentler camber change in the aerofoil. As a result, the attached downward flow region on the BSLF was significantly larger than that on the plain flap. The broader downward flow region eventually resulted in a more substantial up-wash effect of the BSLF on the main element and slat, which increased the overall lift.

5. Improved design of the BSLF using the wall jet AFC method

The low-energy mixing boundary layer is the main reason for the unsatisfactory efficiency of the BSLF. To solve this problem, in this section, the adoption of the wall jet AFC method to improve the performance of the BSLF is investigated.

5.1. Parameter descriptions

In this study, the effects and mechanisms of the wall jet are the key research focus. Therefore, a set of reasonable geometric wall jet-slot parameters was selected and fixed. Referring to the work of Shmilovich and Yadlin (2008) and Yousefi et al. (2014), the layout and geometric parameters of the wall jet slot are presented in Figure 27 and Table 1, respectively.

The momentum coefficient $C_\mu$ was used to measure the wall jet strength. For a continuous wall jet, it is defined as follows (Shmilovich & Yadlin, 2008):

$$C_\mu = \frac{\dot{m}_j v_j}{\frac{1}{2} \rho_{\infty} v_{\infty}^2 c} = \frac{\rho_j v_j^2 w}{\frac{1}{2} \rho_{\infty} v_{\infty}^2 c} = 2 \frac{\rho_j}{\rho_{\infty}} \left( \frac{v_j}{v_{\infty}} \right)^2 \frac{w}{c} \tag{3}$$

For a zero-mass wall jet, the momentum coefficient is defined as follows (De Giorgi et al., 2015):

$$C_\mu = \frac{\dot{m}_j v_j}{\frac{1}{2} \rho_{\infty} v_{\infty}^2 c} = \frac{\rho_j v_j^2 w}{\frac{1}{2} \rho_{\infty} v_{\infty}^2 c} = 2 \frac{\rho_j}{\rho_{\infty}} \left( \frac{v_{RMS}}{v_{\infty}} \right)^2 \frac{w}{c}, \tag{4}$$

where $v_{RMS}$ is the root-mean-square (RMS) value of $v_j$.

In the following sections, the effects of the wall jet position, momentum coefficient, and actuation mode on

| Table 1. Geometric parameters of the wall jet slot. |
|---------------------------------|-----------|
| Parameters | Value |
| $w$ | 0.1%c |
| $d$ | 0.3%c |
| $\theta$ | 30° |
5.2. Effect of the wall jet position

For the wall jet slot position, three options (Jet1, Jet2, and Jet3) were selected, as shown in Figure 28.

The control effect was analyzed at $\alpha = 10^\circ$. Figure 29 shows a comparison of $\Delta C_L$ for the BSLF aerofoils with different slot positions. The results show that Jet1 had...
the worst control effect, and the $C_L$ even decreased. The control effect of Jet2 was the best, with a $\Delta C_L$ of approximately 0.25. The control effect of Jet3 was not apparent, and the $C_L$ slightly changed.

The control effect of the wall jet is reflected in the size of the separation region. Figure 30 shows the flow characteristics of BSLF A under the control of wall jets at various positions. The separation region controlled by Jet2 was
the smallest, whereas that controlled by Jet1 expanded to some extent. For the Jet3 case, the separation size did not change significantly, but the flow structure within the separation region changed, and a new vortex appeared downstream of the jet position.

To further analyse the wall jet control mechanisms at different positions, the velocity profiles of the 10% $c_{local}$ upstream and downstream locations of each slot on aerofoil A were extracted, as shown in Figure 31, where $v_t$ is the local tangential velocity component. Additionally, the local streamline diagram of each slot is also given, which can intuitively reveal the interaction between the wall jet and the mainstream. As shown in these figures, Jet1 was located in a high-speed attached flow area. At this time, the wall jet squeezed into the mainstream with a specific incident angle (30° here), which had slowing and arcing effects on the mainstream. This deceleration of the upper surface flow was responsible for the loss of lift, as shown in Figure 29. Jet2 was in the low-speed attached flow region with a high separation risk. The high-energy wall jet induced and accelerated the upstream and downstream mainstream, effectively controlling the separation. Jet3 was within the separation area, where the mainstream direction at the actuation position was opposite to the wall jet direction. At this time, the energy input into the mainstream was not sufficient to change the separation condition. Therefore, a small attached flow area appeared downstream, inducing a new tiny vortex opposite to the primary vortex; in other words, the separation configuration changed, as shown in Figure 30.

In conclusion, with the same momentum coefficient and arrangement, the wall jet applied near the separation point had the greatest control effect.
The aerodynamic performance of the BSLF aerofoils with Jet2 is shown in Figure 32. After employing Jet2, both the $C_L$ and the lift curve slope of the BSLF aerofoils increased. The lift curve slope was close to that of the MTE aerofoil. The highest control effect was obtained near $\alpha = 10^\circ$ because the actuation position was selected at the separation point in this state. As the separation area reduced, the drag of BSLF aerofoils with Jet2 also reduced.

### 5.3. Effect of the momentum coefficient

The influence of $C_\mu$ was investigated based on the Jet2-controlled BSLF by increasing the jet velocity to enhance $C_\mu$. The selection of the jet velocity in this section was based on the local velocity of the upper surface of the flap. It can be seen from Figure 13 that the range of the local flow velocity on the flap with the slot flow sweeping was approximately $1.0v_\infty - 1.6v_\infty$ (for Section A) and $1.0v_\infty - 1.8v_\infty$ (for Section B). Figure 31(b) shows that for the BSLF without AFC, the local flow velocity near the separation point was only approximately $0.6v_\infty$. Therefore, $1.0v_\infty$ (Jet2$0$), $1.5v_\infty$ (Jet2$1$), and $2.0v_\infty$ (Jet2$2$) were selected as jet velocities to compensate for the local flow velocity loss caused by the slot cancelation, and the corresponding $C_\mu$ values were 0.20%, 0.45%, and 0.80%, as indicated in Table 2. Compared with the $C_\mu$ in the work of other researchers, such as 0.05%–1.28% of Steinfurth and Haucke (2018), 1.5% of Shmilovich and Yadlin (2008), and 0.225%–0.625% of Yousefi et al. (2014), the $C_\mu$ range in the present study (0.20%–0.80%) is almost at a middle position, which can reflect the influence and mechanism of the momentum coefficient change on the control effect.

Figure 33 shows the lift and drag characteristics for the different cases. Increasing $C_\mu$ can significantly improve the lift enhancement ability of BSLF aerofoils. When $C_\mu$ was increased to 0.80%, the lift characteristics of the BSLF aerofoils were equivalent to or even exceeded those of the MTE aerofoils at small and medium angles of attack. The increases in the linear-segment $C_L$ of aerofoils A and B were 0.090 and 0.058, respectively. However, increasing $C_\mu$ did not further improve stall performance. In contrast, the stall angle of attack decreased, and the increase in $C_{L_{\text{max}}}$ was not apparent. Moreover, increasing $C_\mu$ could further reduce the drag of BSLF aerofoils.
Figure 31. Velocity profiles at the 10% $c_{local}$ upstream (left) and downstream (middle) locations of the wall jet slots and their streamline diagrams (right) at $\alpha = 10^\circ$. 

- **Jet1**: High-speed attached flow
- **Jet2**: Low-speed attached flow
- **Jet3**: Separation

Blocking and arching effects
Inducing and accelerating effects
Changing the separation configuration
Figure 34 shows the flow characteristics for different $C_\mu$ values. The separation decreased as the $C_\mu$ increased. When $C_\mu$ reached 0.45%, the flow on the flap became attached. When it reached 0.80%, the flow velocity on the flap was further increased, and the flap efficiency was improved synchronously.

The enhancement of the high-lift ability provided by increasing $C_\mu$ is not unlimited. In the results shown in Figure 33, the stall angle of attack continued to decrease, and the $C_{l_{\text{max}}}$ of each aerofoil was not significantly improved. There seems to be a maximum lift that can be produced by a single aerofoil, and this maximum value was approached earlier by increasing $C_\mu$. Figure 35 depicts the variation in the maximum negative pressure $(-Cp)_{\text{max}}$ on the upper surface of the slat and the main element with $C_\mu$ at different angles of attack. $(-Cp)_{\text{max}}$ can be used as an index of the stall risk and lift enhancement ability of an aerofoil. By increasing $C_\mu$, the $(-Cp)_{\text{max}}$ values on the slat and the main element increased; however, when $C_\mu$ reached a certain value, a clear threshold was reached, and $(-Cp)_{\text{max}}$ did not increase further. After reaching this value, the aerofoil stalled in most states. A stall occurred earlier for higher $C_\mu$ conditions, as shown in Figure 33. This phenomenon indicates that for a particular aerodynamic shape, such as an aerofoil, there is an upper limit on the maximum negative pressure that it can withstand, that is, there is a threshold for the ultimate lift it can provide. After reaching this limit, the performance gains obtained by increasing $C_\mu$ are difficult to further increase. Therefore, a reasonable $C_\mu$ value should be selected to satisfy the lift enhancement requirement, avoid a premature stall, and balance the aerodynamic benefits and energy consumption. The theory of the negative pressure threshold can also explain the stall angle of attack reduction caused by MTE; that is, the MTE makes the angle of attack at which the negative pressure threshold arrives advanced, thus the stall advances.
5.4. Effect of the actuation mode: continuous jet versus zero-mass jet

The previous sections analyzed the control effects and mechanisms of a continuous wall jet. However, a continuous wall jet requires an uninterrupted momentum input, which involves air sources and additional piping. The zero-mass wall jet refers to the AFC technique in which the energy for the mainstream is replenished through periodic blowing and suction, without other mass inputs. Therefore, in this section, the control effect and efficiency of continuous and zero-mass wall jets are compared.

For comparison, $C_\mu$ for the zero-mass jet Jet2Z was the same as that of the basic continuous jet Jet20, that is, 0.20%. The jet velocity of Jet2Z varies according to the sine law, as follows:

$$v_j(t) = v_{jmax} \sin[2\pi f (t - t_{control \ on})]. \quad (5)$$

For a sine signal input, the following relationship can be defined:

$$v_{jRMS} = \frac{v_{jmax}}{\sqrt{2}}. \quad (6)$$

According to Table 2 and Equation (4), to obtain $C_\mu = 0.20\%$, it is required that:

$$v_{jRMS} = v_j = v_\infty, \quad (7)$$

and:

$$v_{jmax} = \sqrt{2}v_\infty. \quad (8)$$

Equations (5) and (8) determine the imposed boundary conditions for $v_j(t)$.

Although the wall jet frequency $f$ is an important parameter, the difference between the zero-mass and continuous jets is the focus of this section. Therefore, an analysis of the influence of $f$ is not included here, and a predetermined value of $f$ is used. The selected value
of \( f \) was consistent with the natural vortex shedding frequency of the BSLF, which was calculated in advance. The jet frequencies of BSLF A and BSLF B were 13 and 16 Hz, respectively.

The calculation was performed using the URANS solver for \( \alpha = 10^\circ \), and the steady RANS solutions were input as the initial files. The jet velocity before the control start time, \( t_{\text{control onset}} = 4 \) s, was 0, and the jet velocity varied according to Equation (5). Considering the high accuracy and less computational time requirements of the simulation (Salih et al., 2019), a time-dependence study was conducted to determine a reasonable time step \( \Delta t \), and the results are shown in Figure 36. The ordinate in the figure is the average value of the periodic \( C_L \) and \( C_D \); the abscissa \( \Delta t \) represents the time step before the wall jet application, and \( i \) represents the time-step numbers per actuation cycle for the zero-mass jet (Jet2Z). According to the results, \( \Delta t = 0.001 \) s and \( i = 100 \) were selected. For comparison, the time-step size of the continuous jet (Jet2C) was consistent with that of Jet2Z. The number of inner iterations per time step was 10, and the total calculation time ensured that each case acceptably converged.

Figure 37 shows the \( C_L \) development before and after the wall jet was used. Because the steady RANS cannot capture the vortex shedding effect (Meunier, 2009), the \( C_L \) values calculated by RANS and URANS were different, as illustrated in the figures. This difference was considered not to affect the conclusion when comparing the jet control effects, which was evaluated by the change in the average value of the calculated \( C_L \) before and after jet application derived by URANS. For Section A, the \( \Delta C_L \) of Jet2C and Jet2Z were 0.1527 and 0.2032, respectively; for Section B, they were 0.1351 and 0.1693, respectively. This means that for Sections A and B, the \( C_L \) increment capabilities of the zero-mass jet were 33.1% and 25.3% higher, respectively, than that of the continuous jet. In addition, the periodic jet significantly increased the fluctuation amplitude of the \( C_L \).

Figure 38 shows the change in the wall jet velocity and \( C_L \) of BSLF A in one actuation cycle. The results indicated that \( C_L \) hardly changed with time under continuous jet control. In contrast, for the zero-mass jet, the \( C_L \) exhibited a periodicity similar to that of the wall jet velocity. However, there was a phase difference between them; that is, the control of the periodic jet exhibited a time lag. This
Figure 35. Variation in $(-C_p)_{\text{max}}$ on the slat and main element with $C_\mu$.

Figure 36. Time-dependence study for the URANS simulations.
occurs because the wall jet essentially injects energy into the boundary layer and then uses the induction and acceleration effects of the high-energy flow to change the flow field structure, thereby affecting the aerodynamic performance. However, these effects require a certain amount of time to affect the upstream and downstream, and thus the control effect exhibits a lag.

To evaluate the control efficiency of the continuous and zero-mass wall jets quantitatively, the following evaluation method was proposed to comprehensively consider the lift enhancement effect and energy consumption. First, the mechanical work of a periodic wall jet in an actuation cycle is defined as follows:

\[
W_j = \frac{T_j}{2} \int_0^1 \frac{1}{2} \dot{m}_j(t) v_j^2(t) \, dt,
\]

where:

\[
\dot{m}_j(t) = \rho_j w v_j(t). \tag{10}
\]

It should be noted that Equation (10) is the jet mass flow rate of the wing per unit span. Then, from Equations (9) and (10), the theoretical power of the wall jet can be derived.

\[
P_j = \frac{W_j}{T} = \rho_j w T \int_0^1 v_j^3(t) \, dt \tag{11}
\]

For a continuous jet, Equations (9)–(11) do not change with time. Finally, the wall jet power required by the unit \( C_L \) increment is defined as the \( P_{CL} \).

\[
P_{CL} = \frac{P_j}{\Delta C_L} \tag{12}
\]

The \( P_{CL} \) of BSLF A and B were calculated and are listed in Table 3. Under the same \( C_{L,\mu} \), the zero-mass jet had a lower \( P_{CL} \), and the relative decreases in the two aerofoils were 9.7% and 4.2%, respectively. This indicates that the control efficiency of the zero-mass jet was higher, and it was more economical.

The difference in the control effect between the continuous and zero-mass jets is due to the different control mechanisms. Figure 39 compares the streamline diagrams and \( C_p \) contours in an actuation cycle; as a comparison, the results for the uncontrolled BSLF A over a \( C_L \) change cycle are also presented.

**Table 3. Differences in \( P_{CL} \) between continuous and zero-mass jets.**

| Jet name | \( P_j \) (kW) | \( \Delta C_L \) | \( P_{CL} \) (kW) | \( \Delta P_{CL} \) (Jet2Z to Jet2C) |
|----------|----------------|----------------|-----------------|-------------------------------|
| BSLF A   | Jet2Z         | 1.9792         | 0.1527          | 12.9612                       |                               |
|          | Jet2C         | 2.3770         | 0.2032          | 11.6980                       | -4.2                          |
| BSLF B   | Jet2Z         | 1.4675         | 0.1351          | 10.8622                       |                               |
|          | Jet2C         | 1.7625         | 0.1693          | 10.4105                       | -9.7                          |
After applying Jet2C, the separation on the BSLF was reduced, and both the flap efficiency and $C_L$ were improved. In addition, the continuous jet played a role in stabilizing the vortex structure on the BSLF. Vortex shedding occurred only at the trailing edge of the BSLF, which had little effect on the upper surface pressure of the aerofoil, thus reducing the $C_L$ fluctuation, as shown in Figure 37.

After applying Jet2Z, the vortex shedding effect was evident in the alternating high-pressure and low-pressure regions. On the whole, the vortex pressure on the Jet2Z-controlled flap was lower, which resulted in a higher $C_L$, although the separation area was not significantly reduced compared with that of the Jet2C-controlled case. In one actuation cycle, the upper surface of the BSLF underwent a process of upstream vortex formation, vortex merging, vortex shedding, and upstream vortex re-formation. The alternating blowing and suction effects of the zero-mass jet caused the continuous formation of new upstream vortices. Compared with the fixed vortex structure in the Jet2C case, the vortex shedding in the Jet2Z-controlled case lowered the BSLF upper surface pressure, and the lift enhancement ability was more satisfactory.

The comparison of the flap pressure distribution given in Figure 40 further illustrates the lift enhancement mechanism of the alternating blowing-suction action of Jet2Z. Because the pressure distribution of the Jet2C-controlled aerofoil slightly changed with time, only one moment is shown for comparison. It can be seen that the suction effect accelerated the upstream flow, which improved the lift to some extent. Moreover, the blowing
effect accelerated the downstream boundary layer and promoted vortex shedding. The negative pressure in the vortex shedding region of the Jet2Z-controlled aerofoil was lower than that of the Jet2C-controlled aerofoil. This blowing-suction synergy provided a better lift-enhancement ability to Jet2Z.

In summary, both the control effect and efficiency of the zero-mass jet are higher than those of the continuous jet, and their action mechanisms are different. However, as the $C_L$ of the Jet2Z-controlled aerofoil fluctuates more drastically, it is necessary to evaluate the impact of this periodic action on the local structure before application. In addition, the actuator system of the zero-mass jet is considerably different from that of a continuous jet. The former generally does not require an external air source and pipelines, thus its comprehensive benefit may be higher than the results here, which requires a detailed system design.

### 5.5. 3D wing study for BSLF

The 3D wing model in Section 3.3, was used to study the application of BSLF. The wall jet was arranged as a spanwise groove, and the application position was along the separation line of the uncontrolled wing at $\alpha = 10^\circ$. Figure 41 shows the aerodynamic performance of BSLF wings with and without a wall jet, and that of the uncontrolled BSLF wing was between the baseline and MTE wings. The lift of the wall jet controlled BSLF wings increased significantly, with $C_{\mu}$ values of 0.45% and 0.80% exceeding the MTE wing. However, as $C_{\mu}$ further increased, $C_L$ and $C_D$ increased simultaneously, leading to a decrease in the lift-to-drag ratio. Therefore, it is necessary to select a small $C_{\mu}$ to obtain a lift enhancement while ensuring a high lift-to-drag ratio during the takeoff phase and choose a large $C_{\mu}$ to provide sufficient lift during the landing phase.

Figure 42 shows the surface streamlines and separation regions of the wings. Consistent with the 2D study results, the wall jet with a $C_{\mu}$ of 0.20% could eliminate part of the flap separation. When $C_{\mu}$ increased to 0.45%, the flap separation could be eliminated entirely. This result shows that the 3D effect has little influence on the jet control effect. If $C_{\mu}$ increases further, the flow field characteristics will not change significantly. However, the lift will be further improved, as shown in Figure 41, reflecting the inducing acceleration effect of the wall jet on the upper surface flow. However, at this time, a further lift enhancement will result in a significant drag increase, which may be caused by the induced drag increase, which is different from the 2D study results.

In summary, the BSLF wing showed superior performance compared to the baseline wing, proving its application potential. At the same time, the control effect of the wall jet was confirmed, and it was less affected by the 3D effect. In addition, it is still crucial to determine a reasonable $C_{\mu}$ because, for a wing, the considerable lift enhancement obtained by increasing $C_{\mu}$ means a non-neglectable drag penalty.

### 6. Conclusions

Given the limitations of the traditional Fowler flap, such as flow separation, noise sources, and exposed mechanisms, this study aims to improve the trailing-edge flap technically and conceptually. A comparative study of typical multi-element aerofoils and wings was conducted to illustrate the generality of the improved design and conclusions. As a passive flow control method, the MTE was adopted to eliminate the separation on the flaps, which significantly improved the performance. Then, a BSLF concept based on an MTE aerofoil was proposed, and a new type of high-lift device with high aerodynamic performance was obtained by applying the wall jet AFC technique. This study elaborated on the design principles, flow mechanisms, aerodynamic characteristics, and parameter effects of these improved designs and concepts. The main conclusions are as follows:

1. The MTE can effectively control the separation on the flap and enhance the lift and drag performance. The deflection design follows the tangent principle, that is, the deflection should be at the position where the MTE extension line is tangential to the upper surface of the flap. For the MTE aerofoils designed according to this principle, the linear-segment $C_L$ increased by 1.2 and 1.4, respectively,
and this increase was 0.79 for a 3D wing. The control mechanisms of the MTE can be summarized as follows: controlling the direction of the slot flow to enhance the sweeping effect, controlling the flow field energy distribution to support the flap boundary layer to withstand the pressure gradient and create a high-energy slot flow attached to the flap, enlarging the circulation, and pushing it forward by increasing the camber and through the inducing effects of various elements. In addition, a stall advance should be solved when the MTE is applied, and the weakening effect caused by the 3D spanwise flow should be considered;

(2) The BSLF is a new type of flap that can eliminate external fairings, which can simplify the mechanisms and reduce cruise drag. Although slot removal leads to a loss of lift, the performance advantage of the BSLF is more than 27% higher than that of the general plain flap;

(3) A wall jet can effectively improve the performance of a BSLF. A wall jet with an appropriate location and adequate strength can allow the BSLF aerofoil and wing to attain an equivalent or even better aerodynamic performance than the MTE aerofoil and wing, reflecting its application potential. Through a detailed study of the BSLF controlled by various wall jets, the following conclusions were obtained.

(a) The control effect was the best when the wall jet position was near the separation point because the inducing and accelerating effects of the high-energy jet on the mainstream could be fully utilized at this time;

(b) Increasing $C_{\mu}$ further improved the control effect, but it also caused an advanced stall and a non-neglectable drag penalty for a wing, which requires further attention;

(c) Compared with the continuous jet, the zero-mass jet with alternating blowing-suction had a higher lift enhancement effect and control efficiency. The results of the two aerofoils show that the lift enhancement effect was 33.1% and 25.3% higher, whereas the power for a unit $C_L$ increment, $P_{CL}$, was 9.7% and 4.2% lower, respectively;

![Figure 41. Aerodynamic characteristics of the BSLF and wall jet controlled BSLF wings.](image-url)
Flow control concepts and technologies provide additional possibilities for the development of high-lift devices. In view of this tendency, this study summarized the shortcomings of Fowler flaps and proposed targeted technical and conceptual improvements. Through meticulous numerical research, the flow control principles at the theoretical level were analyzed and design suggestions at the application level were provided. This study also provides individual enlightenment and engineering significance for high-lift device design for new-generation civil aircraft.

This study mainly focused on the lift enhancement of each trailing-edge flap technology in the design state at moderate angles of attack. In fact, the stall characteristics and $C_{L_{\text{max}}}$ are also essential aspects of high-lift device design. The MTE and other methods in this study may cause the stall angle of attack to decrease, which requires corresponding improvements to the leading-edge slat to delay the stall. Therefore, comprehensive research on the leading-edge and trailing-edge high-lift techniques is a direction that can be further studied.

The application of the wall jet depends on the trade-off between the benefits of the simplified high-lift device and the weight and power requirements of the AFC system. Specifically, it is necessary to study the wall jet mode with a simple structure and high control efficiency, and to study the arrangement of the AFC system on the aircraft to maximize the control effect. For the former, the current study compared the continuous jet and zero-mass jet; for the latter, the current study analyzed the wall jet positional influence. Moreover, the reliability and robustness study of the wall jet system and the coupling problem with the aircraft control system need to be further studied.

Future research will consider two aspects: the first is the structural design and strength analysis of a 3D BSLF, and the second is the design and aircraft-level benefit evaluation of a BSLF–AFC high-lift system.
Disclosure statement
No potential conflict of interest was reported by the author(s).

Funding
This work was supported by the Fundamental Research Funds for the Central Universities (Nos. 3102019J009 and G2016KY0002).

References
Aley, K. S., Guha, T. K., & Kumar, R. (2020). Active flow control of a high-lift supercritical airfoil with microjet actuators. AIAA Journal, 58(5), 2053–2069. https://doi.org/10.2514/1.J058939
Anderson, J. D. (2010). Fundamentals of aerodynamics. McGraw-Hill Education.
Cai, Y., Gao, Z., Chakraborty, I., Briceno, S., & Mavris, D. (2018). System-level assessment of active flow control for commercial aircraft high-lift devices. Journal of Aircraft, 55(3), 1200–1216. https://doi.org/10.2514/1.C034401
Chin, V. D., Peters, D. W., Spaid, F. W., & Mcghee, R. J. (1993). Flowfield measurements about a multi-element airfoil at high Reynolds numbers. In AIAA 24th fluid dynamics conference (p. 3137).
Chu, H., Zhang, B., Chen, Y., Li, Y., & Mao, J. (2012). Investigation of micro vortex generators on controlling flow separation over SCCH high-lift configuration. Science China Technological Sciences, 55(7), 1943–1953. https://doi.org/10.1007/s11431-012-4850-5
De Giorgi, M. G., De Luca, C. G., Ficarella, A., & Marra, F. (2015). Comparison between synthetic jets and continuous jets for active flow control: Application on a NACA 0015 and a compressor stator cascade. Aerospace Science and Technology, 43, 256–280. https://doi.org/10.1016/j.ast.2015.03.004
Dobrzynski, W. (2010). Almost 40 years of airframe noise research: What did we achieve? Journal of Aircraft, 47(2), 353–367. https://doi.org/10.2514/1.44457
Finez, A., Jacob, M., Jondeau, E., & Roger, M. (2010, June). Broadband noise reduction with trailing edge brushes. In 16th AIAA/CEAS aeroacoustics conference (p. 3980). https://doi.org/10.2514/1.3980
Ghalandari, M., Shamshirband, S., Mosavi, A., & Chau, K.-W. (2019). Flutter speed estimation using presented differential quadrature method formulation. Engineering Applications of Computational Fluid Mechanics, 13(1), 804–810. https://doi.org/10.1080/19942060.2019.1627676
Hartwich, P. M., Camacho, P., El-Gohary, K., Gonzales, A. B., Lawson, E. L., & Shimilovich, A. (2017, January). System-level trade studies for transonic transports with active flow control (AFC) enhanced high-lift systems. In 55th AIAA aerospace sciences meeting (p. 0321). https://doi.org/10.2514/6.2017-0321
Hartwich, P. M., Dickey, E. D., Scalfani, A. J., Camacho, P., Gonzales, A. B., Lawson, E. L., Mairs, R. Y., & Shimilovich, A. (2014). AFC-enabled simplified high-lift system integration study (Report No. NF1676L-19609). NASA.
Hartwich, P. M., Shimilovich, A., Lacy, D. S., Dickey, E. D., Scalfani, A. J., Sundaram, P., & Yadlin, Y. (2016). Refined AFC-enabled high-lift system integration study (Report No. NF1676L-23752). NASA.
Jimenez, H., Burdette, G., Schutte, J., & Mavris, D. (2011, September). Probabilistic technology assessment for NASA environmentally responsible aviation (ERA) vehicle concepts. In 11th AIAA aviation technology, integration, and operations (ATIO) conference (p. 6967). https://doi.org/10.2514/6.2011-6967
Kim, S., Alonso, J. J., & Jameson, A. (2002). Design optimisation of high-lift configurations using a viscous continuous adjoint method. In 40th AIAA aerospace sciences meeting & exhibit (p. 0844). https://doi.org/10.2514/6.2002-844
Liu, P., Li, D., Qu, Q., & Kong, C. (2019). Two-dimensional new-type high-lift systems with link/straight track mechanism coupling downward deflection of spoiler. Journal of Aircraft, 56(4), 1524–1533. https://doi.org/10.2514/1.C035145
Ma, X., Shi, Y., & Song, W. (2020, June). Aerodynamic and aeroacoustic analysis of scch models of four high-lift configurations near stall angle of attack. In AIAA aviation 2020 forum (p. 2508). https://doi.org/10.2514/6.2020-2508
Melton, L. T. G. P., Lin, J. C., Hannon, J., Koklu, M., Andino, M. & Paschal, K. B. (2019, June). Sweeping jet flow control on the simplified high-lift version of the common research model. In AIAA aviation 2019 forum (p. 3726). https://doi.org/10.2514/6.2019-3726
Meunier, M. (2009). Simulation and optimisation of flow control strategies for novel high-lift configurations. AIAA Journal, 47(5), 1145–1157. https://doi.org/10.2514/1.38245
Nguyen, N. T., Precup, N., Livne, E., Urnes, J. M., & Lebofsky, S. (2015). Wind tunnel investigation of a flexible wing high-lift configuration with a variable camber continuous trailing edge flap design. In 33rd AIAA applied aerodynamics conference (p. 2417). https://doi.org/10.2514/6.2015-2417
Rumsey, C. L., Gatski, T. B., Ying, S. X., & Bertelrud, A. (1998). Prediction of high-lift flows using turbulent closure models. AIAA Journal, 36(5), 765–774. https://doi.org/10.2514/2.435
Rumsey, C. L., & Ying, S. X. (2002). Prediction of high lift: Review of present CFD capability. Progress in Aerospace Sciences, 38(2), 145–180. https://doi.org/10.1016/S0376-0421(02)00003-9
Salih, S. Q., Aldlemy, M. S., Rasani, M. R., Ariffin, A. K., Ya, T. M. Y. S. T., Al-Ansari, N., Yaseen, Z. M., & Chau, K. W. (2019). Thin and sharp edges bodies-fluid interaction simulation using cut-cell immersed boundary method. Engineering Applications of Computational Fluid Mechanics, 13(1), 860–877. https://doi.org/10.1080/19942060.2019.1652209
Shmilovich, A., & Yadlin, Y. (2008). Flow control for the systematic buildup of high-lift systems. Journal of Aircraft, 45(5), 1680–1688. https://doi.org/10.2514/1.35327
Smith, A. M. O. (1975). High-lift aerodynamics. Journal of Aircraft, 12(6), 501–530. https://doi.org/10.2514/3.59830
Steinfurth, B., & Haucke, F. (2018). Coherent structures in the actively controlled wake of a high-lift configuration. AIAA Journal, 56(10), 3848–3856. https://doi.org/10.2514/1.J057094
Streett, C., Casper, J., Lockard, D., Khorrami, M., Stoker, R., Elkoby, R., Wennenman W., Underbrink, J., Wennenman, W. & Underbrink, J. (2006, January). Aerodynamic noise reduction for high-lift devices on a swept wing model. In 44th AIAA aerospace sciences meeting and exhibit (p. 212). https://doi.org/10.2514/6.2006-212
Strüber, H. (2014, September). The aerodynamic design of the A350 XWB-900 high lift system. In 29th international congress of the aeronautical science.

Urnes, J., & Nguyen, N. (2013, January). A mission adaptive variable camber flap control system to optimise high lift and cruise lift to drag ratios of future N + 3 transport aircraft. In 51st AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition (p. 214). https://doi.org/10.2514/6.2013-214

Vatsa, V. N., Duda, B. M., Lin, J. C., Melton, L. G. P., & O’Connell, M. (2018, June). Numerical simulation of a simplified high-lift CRM configuration embedded with fluidic actuators. In 2018 Applied aerodynamics conference (p. 3063). https://doi.org/10.2514/6.2018-3063

Wang, J., Li, Y., & Choi, K. S. (2008). Gurney flap—Lift enhancement, mechanisms and applications. Progress in Aerospace Sciences, 44(1), 22–47. https://doi.org/10.1016/j.paerosci.2007.10.001

Wang, W., Liu, P., Tian, Y., & Qu, Q. (2016). Numerical study of the aerodynamic characteristics of high-lift droop nose with the deflection of fowler flap and spoiler. Aerospace Science and Technology, 48, 75–85. https://doi.org/10.1016/j.ast.2015.10.024

Wang, X., Wang, F., & Li, Y. (2011). Aerodynamic characteristics of high-lift devices with downward deflection of spoiler. Journal of Aircraft, 48(2), 730–735. https://doi.org/10.2514/1.C031301

Wei, B., Wu, Y., Liang, H., Su, Z., & Li, Y. (2020). Flow control on a high-lift wing with microsecond pulsed surface dielectric barrier discharge actuator. Aerospace Science and Technology, 96, 105584. https://doi.org/10.1016/j.ast.2019.105584

Yousefi, K., Saleh, R., & Zahedi, P. (2014). Numerical study of blowing and suction slot geometry optimisation on NACA 0012 airfoil. Journal of Mechanical Science and Technology, 28(4), 1297–1310. https://doi.org/10.1007/s12206-014-0119-1

Yu, G., Li, D., & Zhang, Z. (2020). Numerical simulation for the differences between FTN/WPN engine models aerodynamic influence on BWB300 airframe. Engineering Applications of Computational Fluid Mechanics, 14(1), 566–579. https://doi.org/10.1080/19942060.2020.1733093

Zhang, X. (2010). Airframe noise: High lift device noise. In R. Blockley & W. Shyy (Eds.), Encyclopedia of aerospace engineering (pp. 3541–3551). John Wiley & Sons.