

Aerodynamic Assessment of Surface-Normal Active Flow Control for Lift Enhancement on the High-Lift Common Research Model

Seyedeh Sheida Hosseini*

NASA Ames Research Center, Moffett Field, CA 94035

C. P. van Dam†

University of California Davis, Davis, CA 95616

Shishir A. Pandya‡

NASA Ames Research Center, Moffett Field, CA 94035

This study explores aerodynamic feasibility of small surface-normal pneumatic jets (microjets) for lift enhancement on the high-lift Common Research Model. To date, lift enhancement studies using microjets have been conducted at wind tunnel Reynolds numbers less than three and half million. This paper computationally investigates microjet effects at a flight Reynolds number of 24.6 million. Prior to microjet activation, it is shown that flow features such as trailing edge (TE) flow separation on both inboard and outboard flaps have noticeable sensitivity to Reynolds number. At the flight Reynolds number, the onset of TE flow separation shifts downstream resulting in less flow separation compared to at the wind tunnel Reynolds number of 3.26 million. The effects are insignificant for lift enhancement due to microjet on the inboard flap. However, the effects are significant for lift enhancement on the outboard flap. Microjets are shown to be more effective in circulation control on the outboard flap at the higher Reynolds number. For a microjet with velocity ratio of one, lift enhancement is increased by 17% at the flight Reynolds number. This highlights the sensitivity of microjet performance to the flow features of the configuration it is implemented on. Microjet lift enhancement trends at both Reynolds numbers are found to be consistent in their ability to move the lift curve upwards in the linear regime, with the lift enhancement related to microjet momentum coefficient through $\Delta C_L = K\sqrt{C_\mu}$. Analysis of the impact microjets have on drag shows that microjets improve the configuration's Oswald efficiency by 5.4% and 2.5% at the wind tunnel and flight Reynolds numbers respectively, while providing lift enhancement. Microjet effects on the trim drag are found to be less than one percent of the total drag. The results of this study highlight the potential of small surface-normal pneumatic jets for improved performance at high-lift conditions.

Nomenclature

Symbols

α	angle of attack	C_L	lift coefficient
$\dot{m}$	mass flow rate	C_{Lmin}	lift coefficient for C_{Dmin}
η	spanwise station in fraction of wingspan/2	C_p	pressure coefficient
ρ	density	C_μ	microjet momentum coefficient
AR	wing aspect ratio	C_{Dmin}	drag coefficient at the minimum lift coefficient
C_D	drag coefficient	c_{ref}	Reference chord
		e	Oswald efficiency

*Research Aerospace Engineer, Computational Aerosciences Branch, M/S 258-5. Member AIAA.

†Professor Emeritus, Department of Mechanical and Aerospace Engineering. Associate Fellow AIAA.

‡Research Scientist, Computational Aerosciences Branch, M/S 258-2. AIAA Senior Member.

h_j	microjet width	Subscripts	
K	microjet lift enhancement constant	∞	freestream value
M	Mach number	jet	microjet value
Re	Reynolds number		
S	reference area		
U	flow velocity		
MAC	mean aerodynamic chord		

I. Introduction

WING design for efficient flight remains a challenging task because transport airplanes must operate efficiently over a wide range of airspeeds, weights, and altitudes. For most transport airplanes, takeoff and landing segments comprise a small percentage of the total flight/block time and yet when it comes to airplane safety, size and economics, high-lift systems play a critical role. High-lift surfaces such as slats and flaps are utilized during takeoff and landing to generate higher lift coefficients to allow for reduced airspeeds and therefore takeoff and landing distances to accommodate various airports across the globe. The higher lift coefficients at takeoff and landing generated by these high-lift surfaces enable smaller wings and hence lower drag during cruise. Transport airplanes are at cruise for the majority of their service time, thus lower cruise drag leads to greener and more efficient flight. In addition to reducing the wing size, high-lift devices play an important role in commercial aviation to ensure commonality, such that various members of the same family group may have widely varying fuselage lengths. A longer fuselage introduces challenges such as increasing the risk of tail strike during takeoff or landing. To mitigate such problems, flaps must additionally be designed to be effective at higher deflections. This is required to ensure that elongated airplanes do not have a higher unstuck speed on takeoff and higher touchdown speed on landing as a result of angle of attack limitations imposed by the tail ground clearance angle.

The higher flap deflections required by tail clearance angle limitations result in higher flap loads, which becomes critical for the design of support elements and flap fairings. Another design concern is that for some airplane family members increased flap deflection may not generate the necessary lift at the angle of attack governed by the tail clearance angle; instead an increase in landing gear height may be required. If the landing gear height cannot be increased, a redesign of the high-lift system (e.g., from a single- to two-element flap) may be necessary. Such a redesign increases the recurring and non-recurring costs affecting the ecosystem around that class of airplane such that manufacturing, certification, operation, and maintenance of the particular airplane family is now influenced. The issue of tail clearance angle has been widely studied in the industry and Meredith [1] points out that for a generic twin-engine transport a “0.10 increase of lift coefficient at constant angle of attack is equivalent to reducing the approach attitude by one degree.” For a given tail clearance angle, Meredith converted this to an allowable 14 in. landing gear height reduction and a resulting weight savings of 1400 lb.

In the recent years agencies world-wide have set goals to significantly improve aviation efficiency and environmental performance through programs such as NASA’s ARMD Strategic Thrust 3: Ultra- Efficient Commercial Vehicles [2], Flight path 2050 by the European Union [3], and ICAO’s Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [4]. In response, a wide array of technologies are being investigated to assess potential applications for substantial reduction of aircraft structural weight, CO₂ emissions and fuel burn. Active Flow Control (AFC) is one of these technologies which has gained interest as it offers the potential to adaptively and rapidly change aerodynamic characteristics of lifting surfaces without the use of conventional control surfaces. High-lift systems are complex and heavy, and improvements to them can substantially reduce structural weight. From an aerodynamic perspective, AFC technologies for high-lift systems could be investigated with two interrelated goals in mind: enabling separation mitigation and enabling load control - with the pursuit of either positively or negatively affecting the other. The objective is to find an AFC approach which attains overall favorable performance while satisfying the relevant constraints.

The AFC topic investigated in this paper addresses direct lift-control in the linear regime of the lift curve using small surface-normal pneumatic jets – so called microjets – on high-lift systems of civil transport airplanes. Much of the computational and experimental research on AFC for civil transport airplane high-lift systems is performed at chord Reynolds number well below typical flight Reynolds numbers of 15 to 25 million. Therefore, an investigation of Reynolds number effects on AFC trends is necessary to compare results from these lower Reynolds number studies

and those of full-scale flight. In addition, AFC impact on aircraft efficiency must be evaluated to assess technology's potential for sustainability goals. Specifically, this work addresses the sensitivity of microjet's performance to Reynolds number, develops an Oswald efficiency analysis to address microjet's impact on aircraft efficiency and investigates microjet's impact on aircraft trim drag. In Section II, the computational methodology and a validation study with the experimental data from the NASA LaRC 14-by 22-Foot Subsonic Tunnel test [5] for the high-lift CRM configuration [6] are discussed. In Sections III.A-III.D, sensitivity of microjet's lift enhancement trends to Reynolds number is addressed. In Section III.E, an Oswald efficiency analysis is introduced for airplanes with significant wing camber and microjet's impact on airplane efficiency is investigated. In Section III.F, microjet's impact on trim drag is investigated.

II. Computational Methodology

The baseline geometry considered in this work is the high-lift Common Research Model (CRM)[7]. The CRM is a publicly available geometry that was designed to be representative of modern civil transport jets for world-wide open research dialogues in the aerosciences community. The high-lift CRM represents the landing configuration and has been studied for a series of AIAA high-lift workshops. For the purposes of this paper, the wing/body configuration from the 3rd AIAA CFD High-Lift Prediction Workshop (HiLiftPW-3) [6] is selected, for which the slat and flaps are deployed at 30° and 37° , respectively. As depicted in Figure 1, this selected geometry does not have a nacelle, pylon, empennage, nor slat and flap support brackets. The geometry also contains a full chord gap between its flaps as shown in Figure 1. Prior work [8] by the authors has provided extensive comparisons of computational results and the results shared at HiLiftPW-3, showing good agreement. In this paper, validation against wall-corrected experimental data which have recently become publicly available is performed.

The computational grid for the high-lift CRM wing/body model was originally constructed by William Chan (NASA Ames) with four grid resolutions (coarse, medium, fine and extra fine), which are publicly available on the HiLiftPW-3 website [6]. For this paper, the medium grid resolution is selected as the baseline grid because the computational force values and the flow features shared at the workshop did not change significantly with increasing grid resolution beyond the medium grid, while the computational cost increased noticeably. To properly model microjet effects with proper grid resolution, grid refinement at the inboard and outboard flap trailing edges on the pressure side was found to be necessary. The Chimera Grid Tools [9] software was utilized to refine the flap grids, depicted in Figure 2, increasing the grid size by about 3 million grid points for an overall grid size of about 68.5 million.

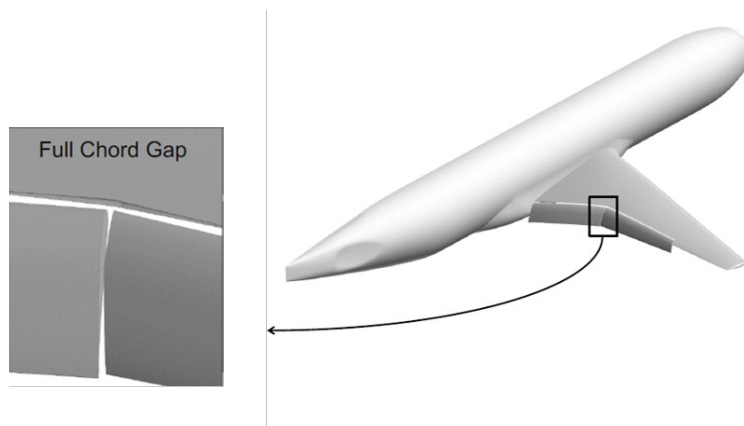


Fig. 1 High-lift CRM wing body configuration used in this study.

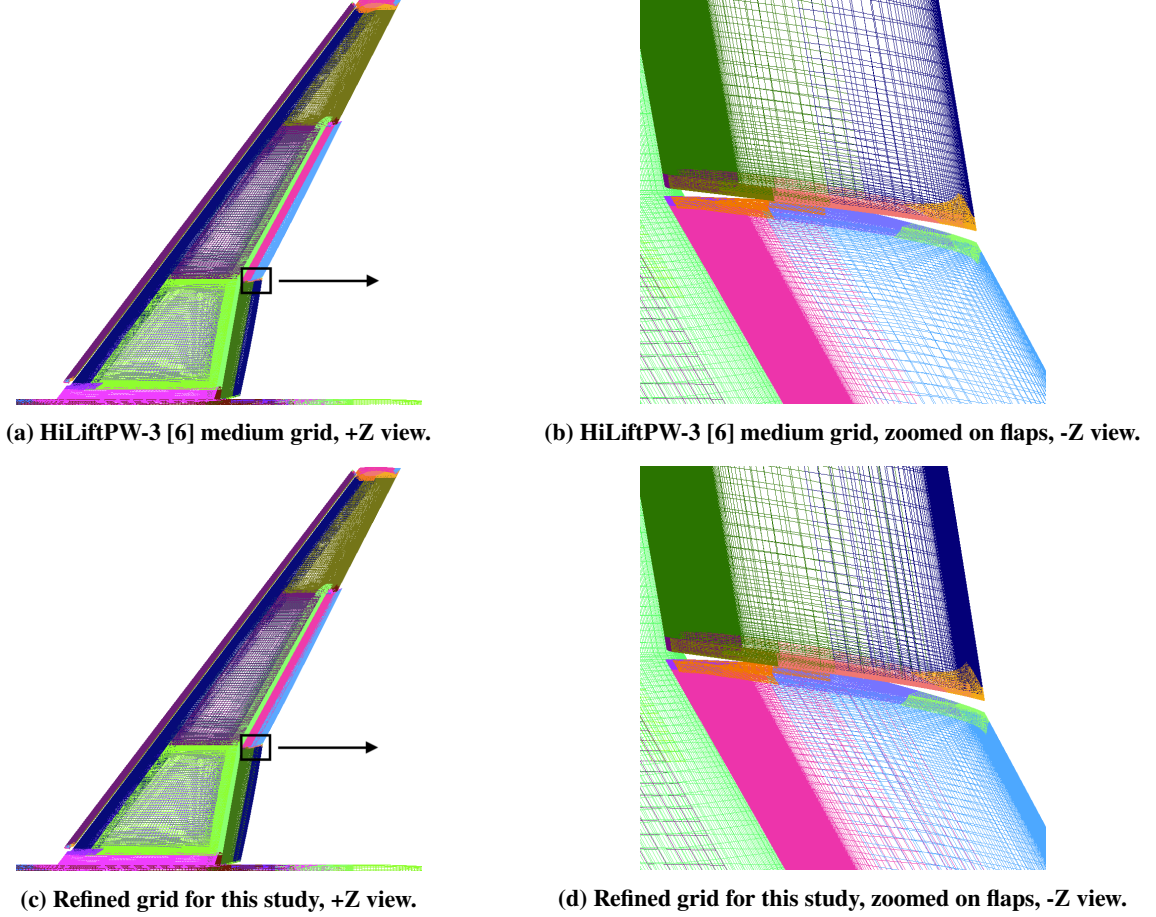


Fig. 2 High-lift CRM grid refinement for microjets studies in this paper. Flap grids on the lower surface in the vicinity of the microjets are refined compared to the HiLiftPW-3 grid with medium resolution.

NASA’s OVERFLOW-2 [10] code was used to solve the Reynolds-averaged Navier-Stokes equations on the computational grid. The 3rd order Roe upwind scheme was used to discretize the spatial terms, and the solution was advanced in time using the F3D Steger-Warming 2-factor scheme. The turbulence effects were modeled with the SA model with RC and QCR2000 corrections. Mesh connectivity was established using Domain Connectivity Function routines [10] and 432 Haswell cores were employed per solution run on NASA’s Pleiades supercomputer. To confirm that grid refinement is not artificially effecting the solution, an initial study was performed comparing computational results between the original and the refined HiLiftPW-3 grid at $\alpha = 8.0^\circ$, $Re_{MAC} = 3.26 \times 10^6$ and $M_\infty = 0.20$. Table 1 summarizes the effects on the integrated aerodynamic forces. For the details of this grid comparison study such as sectional pressure profiles and the flow visualisations please refer to Hosseini et al [8].

Table 1 Integrated force coefficients using the original workshop grid and the refined grid for the current study at $\alpha = 8.0^\circ$, $Re_{MAC} = 3.26 \times 10^6$ and $M_\infty = 0.20$.

	C_L	C_D
Refined medium grid (present study)	1.752	0.1698
HiLiftPW-3 [6] original medium grid	1.753	0.1700

Next, computational results were validated against the experimental data from the NASA LaRC 14-by 22-Foot Subsonic Tunnel test [5]. The wind tunnel (WT) test was performed with natural transition on the model and it provided wall-corrected lift, drag and pitching moment curves at $Re_{MAC} = 3.26$ million and $M_\infty = 0.20$ as well as pressure profiles across the wing span at $\alpha = 7.8^\circ$. Based on the balance accuracy, the reported instrumentation uncertainty was estimated to be within 0.01 for the lift coefficient, 0.0040 for the drag coefficient, and 0.0035 for the pitching moment coefficient. For this computational validation study, pressure profiles were compared at three spanwise locations illustrated in Figure 3. Note that these spanwise locations are relative to the main wing element. Using the pressure port locations and the planes of deployment, corresponding pressure profiles for slat and flaps were extracted from the computational results for comparisons with the WT data.

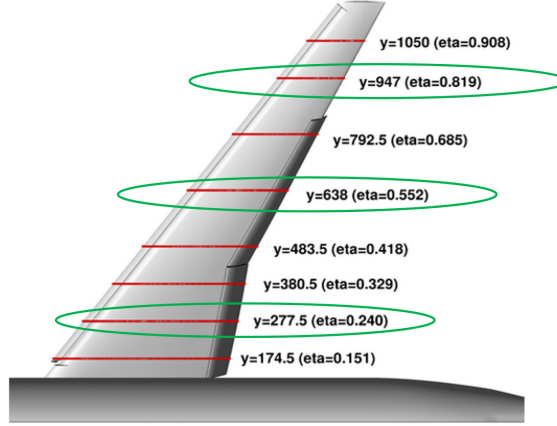


Fig. 3 Pressure cut locations along the wingspan. The mean aerodynamic chord is defined at $\eta = 0.41$.

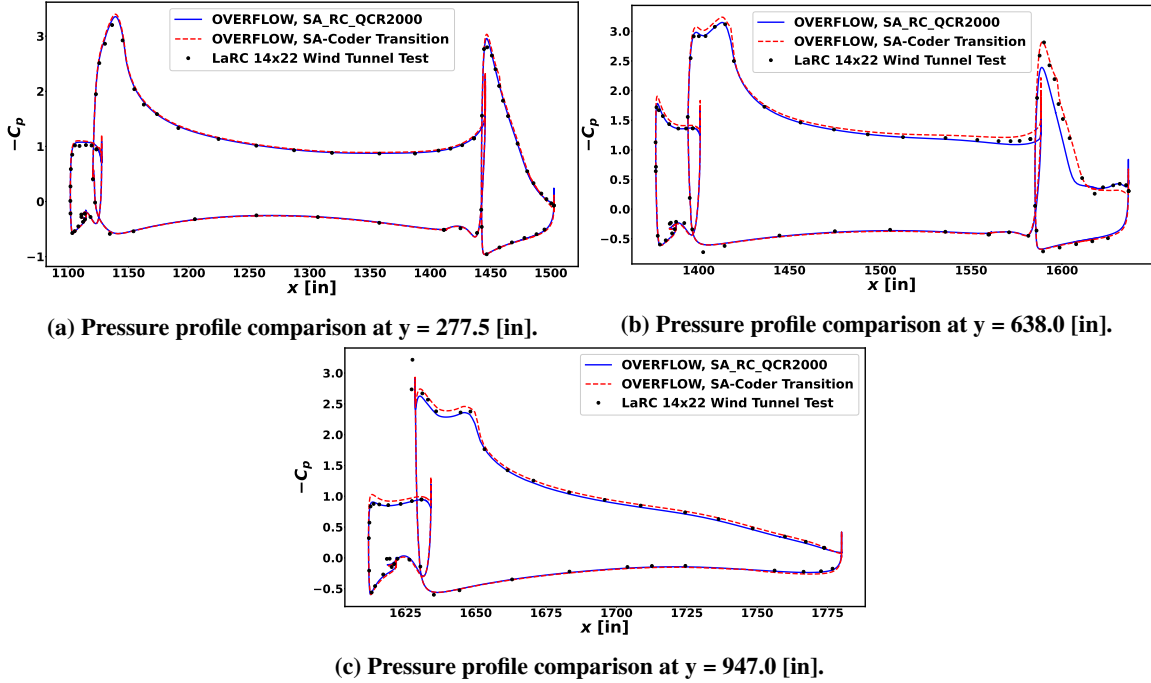


Fig. 4 Pressure profile comparisons between OVERFLOW and WT[5] results at $\alpha = 7.8^\circ$, $Re_{MAC} = 3.26 \times 10^6$ and $M_\infty = 0.20$. Solid blue lines represent the data from a fully turbulent computational simulation. Dashed red lines represent the data from a computational simulation with a laminar to turbulent flow transition model incorporated. Black filled circles represent the WT data.

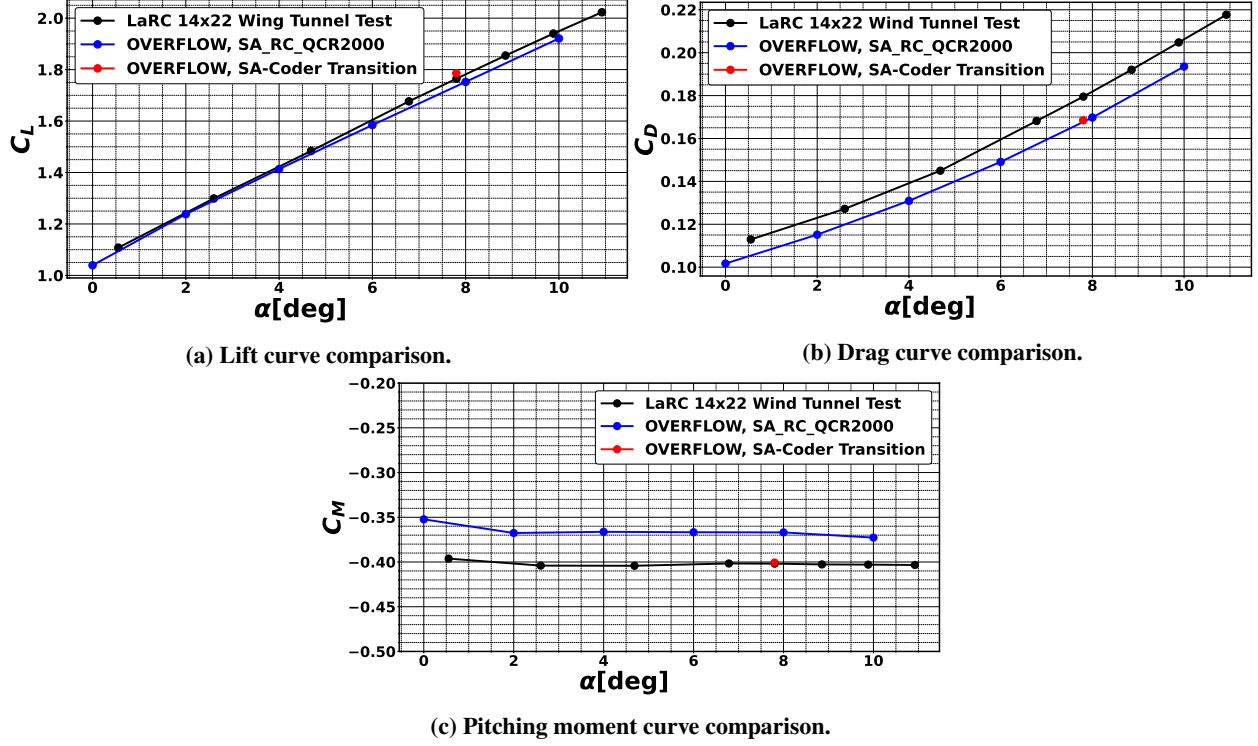


Fig. 5 Integrated force comparisons between OVERFLOW and WT[5] results at $Re_{MAC} = 3.26 \times 10^6$ and $M_\infty = 0.20$. Blue line represents the data from a fully turbulent computational simulation. Red filled circle represent is the solution at $\alpha = 7.8^\circ$ from a computational simulation with a laminar to turbulent flow transition model incorporated. Black line represents the WT data.

Figure 4 presents pressure profile comparisons at $\alpha = 7.8^\circ$. The fully turbulent computational results predict pressure profiles similar to the experimental results at the inboard and outboard locations. However, the suction peak on the outboard flap is found to be noticeably under predicted. Since the flow over the model was not tripped in the WT test, the OVERFLOW simulation at $\alpha = 7.8^\circ$ was repeated with the SA-Coder[11] transition model. With the transition model incorporated, the computational pressure profiles are found to be in better agreement with the WT results. As transition locations at the WT test were not documented, agreement between the computational and experimental transition locations could not be confirmed.

To further assess the computational setup, an angle of attack study was performed for lift, drag and pitching moment comparisons. The turbulent effects were simulated using the fully-turbulent model for the angle of attack study, and the simulation at $\alpha = 7.8^\circ$ was repeated with the SA-Coder[11] transition model. It is found that incorporating transition modeling leads to better agreement between the computational and WT pressure profiles. Also, transition modeling brings the integrated pitching moment much closer to the experiment, lift becomes slightly closer to the experiment and effect on drag is insignificant as depicted in Figure 5.

While the computational and experimental lift values are found to be similar using the fully turbulent model, the difference between the computational and experimental drag and pitching moment values is significant. It is of note that the computational lift, drag and pitching moment in this paper are in agreement to the computational results shared at the HiLiftPW-3 [6]. Therefore, the discrepancy seen between the computational and experimental data for drag is likely associated with the configuration differences. The WT model incorporated 15 slat brackets and three flap fairings that were not included in the computational model. Thus, the under prediction of drag is most likely due to the lack of these support elements in the computational configuration. The discrepancy seen between the computational and experimental data for pitching moment is associated with the minor differences seen in lift. Small differences in lift multiplied by the moment arm can result in significant differences in pitching moment. Therefore, the more nose down pitching moment for the experimental data depicted in Figure 5c is expected as a result of the slightly higher experimental lift values shown in Figure 5a. With turbulent effects simulated using the transition model at $\alpha = 7.8^\circ$, computational and experimental lift values are slightly in more agreement and that leads to the better agreement of pitching moment values.

Fully turbulent simulations were adopted for the remainder of the study due to the lack of availability of experimental transition locations, and because the primary goal of our study in this paper is to investigate trends in the aerodynamic performance characteristics as a result of microjets.

III. Reynolds Number Sensitivity Study

Often computational and experimental AFC research on airplane high-lift systems is performed at Reynolds numbers around three to four million, well below full-scale Reynolds numbers of 15 – 25 million for commercial transport airplanes. To ensure dynamic similarity, Reynolds number sensitivity studies are performed to compare the flow features on the HiLiftPW-3 configuration at both a flight Reynolds number of 24.6 million and a wind tunnel Reynolds number of 3.26 million. The flow features on the baseline geometry are presented in section A while the studies concerning the sensitivity of microjet effectiveness to changes in Reynolds number are addresses in the following sessions. In those studies, trends such as the microjet lift enhancement relationship $\Delta C_L = K\sqrt{C_{\mu}}$ and microjet-induced lift enhancement through a shift in the linear region of the lift curve are examined. An Oswald efficiency analysis is also presented along with an investigation into effects of microjets on the aerodynamic efficiency and trim drag of the configuration.

A. Computational Setup

Initial wall-spacing plays a critical role when it comes to modeling the boundary layer in turbulent flow simulations. To check if viscous wall spacing refinement on the computational grid generated for studies at $Re_{MAC} = 3.26$ million was necessary for studies at the flight Reynolds number, a y^+ study was performed. The parameter y^+ is a non-dimensional wall distance for wall-bounded flows and it's value is recommended to be close to one in order to model the boundary layer accurately. From a study on OVERFLOW solution at $Re_{MAC} = 24.6$ million using the grid generated for $Re_{MAC} = 3.26$ million, y^+ was found to be much larger than one as depicted in Figure 6a. Therefore, the initial wall-spacing on the grid generated for studies at $Re_{MAC} = 3.26$ million was refined for the studies at $Re_{MAC} = 24.6$ million. This viscous wall spacing refinement ensured y^+ would be mostly around one across the geometry surface as depicted in Figure 6b, and increased the computational grid size to 128M for the studies at the flight Reynolds number. Grid resolution sensitivity will be further investigated in future studies.

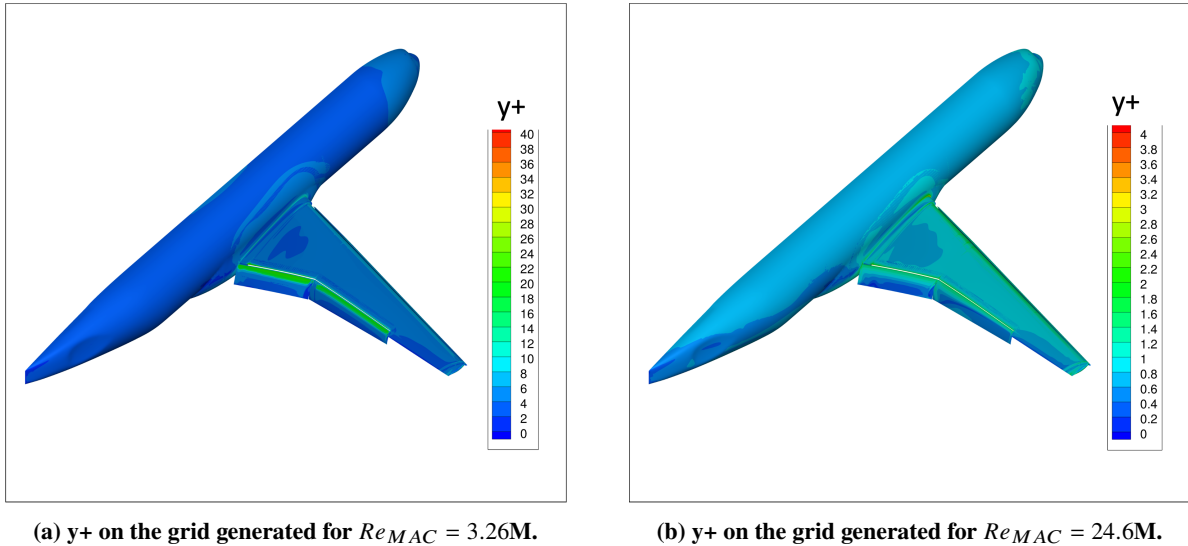


Fig. 6 Dimensionless wall distance (y^+) surface contour at $\alpha = 8.0^\circ$, $Re_{MAC} = 24.6$ million and $M_\infty = 0.20$. (a) y^+ contour on the solution at $Re_{MAC} = 24.6$ million using the grid generated for $Re_{MAC} = 3.26$ million. (b) y^+ contour on the solution at $Re_{MAC} = 24.6$ million using the grid generated for $Re_{MAC} = 24.6$ million.

After adjusting the surface-normal grid distributions, OVERFLOW simulations were carried at $Re_{MAC} = 24.6$ million to investigate Reynolds number effects on the aerodynamics of the HiLiftPW-3 configuration of the high-lift CRM model. These studies incorporated the same OVERFLOW computational setup as used for the studies at $Re_{MAC} = 3.26$ million to ensure the differences in the solutions reflect the differences in Reynolds number rather than the computational

setup. Comparison of the flow features at both Reynolds numbers in Figure 7 shows that with increasing the Reynolds number from $Re_{MAC} = 3.26$ million to $Re_{MAC} = 24.6$ million, the onset of trailing edge flow separation on the inboard and the outboard flaps shifts downstream. On the inboard flap, trailing edge flow separation is moderate at both Reynolds numbers, and with increasing the Reynolds number the flow separation is mostly mitigated. On the outboard flap, trailing edge flow separation is significant and the separation line is found to move downstream by approximately 5-10% of the flap chord with increasing the Reynolds number. This sensitivity of the trailing edge flow separation to Reynolds number is a topic worth exploring within the context of AFC as mitigation of trailing edge flow separation via application of AFC technologies is overstated at wind tunnel Reynolds numbers less than three and half million compared to those of flight conditions. However, for AFC with a circulation control focus similar to the technology studied in this paper, the trends can be opposite. The studies in sections III.B to III.F seek to understand if less trailing edge flow separation at flight Reynolds number can lead to increased microjet enabled performance improvements compared to the trends obtained at the WT Reynolds number.

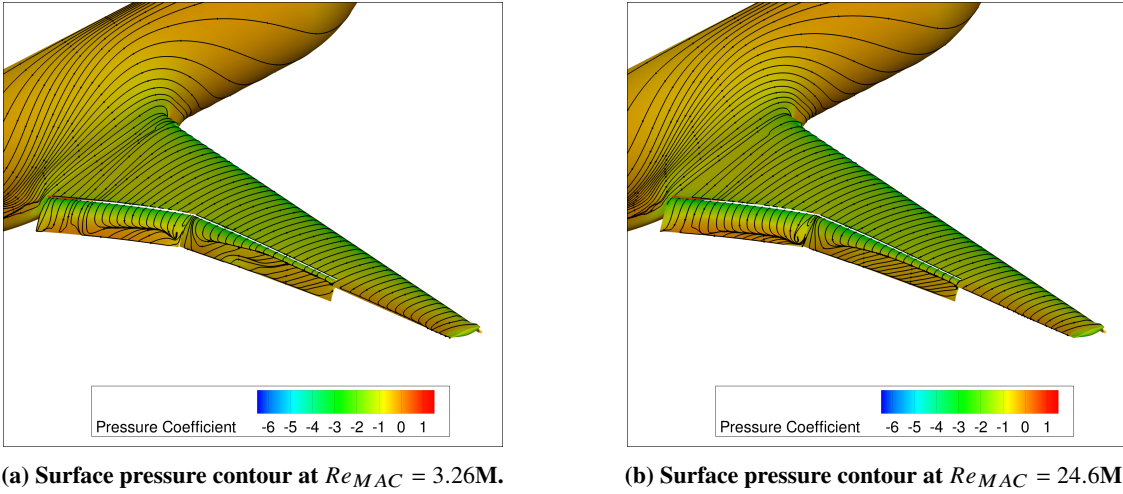


Fig. 7 Comparison of surface pressure contours at WT and flight Reynolds numbers at $\alpha = 8.0^\circ$ and $M_\infty = 0.20$.

B. Microjet Implementation on the High-Lift CRM Geometry

Microjets are usually characterized by a non-dimensional force coefficient C_μ (see Equation 1) which describes the non-dimensional force added into the free stream due to jet momentum. In Equation 1, u_i and u_j are velocity vector components in the Cartesian directions, n_j is the surface-normal vector direction, and S is the CRM reference wing area.

$$C_\mu = \frac{\int \rho u_i u_j n_j dA}{\frac{1}{2} \rho_\infty U_\infty^2 S} \quad (1)$$

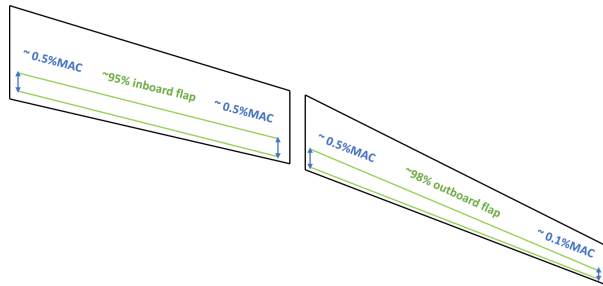


Fig. 8 Illustration of microjet implementation on the lower surface of high-lift CRM flaps (left – inboard, right – outboard), image is not to scale.

To be consistent with previous studies [8], continuous blowing microjets are modeled with OVERFLOW's uniform surface transpiration boundary condition U_{jet}/U_∞ on the lower surface of the flaps. Because there are cap grids at the flap ends which the transpiration boundary condition cannot extend, the microjet slot covers about 95% of span on the inboard flap and about 98% of span on the outboard flap. The layout of the microjet is depicted in Figure 8. The microjet slot width is set to about 0.5% of the mean aerodynamic chord (MAC) on the inboard flap. On the outboard flap, the microjet slot width narrows to about 0.1% of the MAC to allow for a more consistent ratio of local microjet width to the wing chord across the span.

C. Momentum Coefficient Sensitivity Study

In this section, microjets are implemented on the lower surface of both inboard and outboard flaps for a C_μ range of 0 to 0.015. Figure 9 shows that with increasing microjet input, the corresponding lift enhancement increases at both Reynolds numbers. The lift enhancement relationship is similar to the $\Delta C_L = K\sqrt{C_\mu}$ relationship [8, 12, 13], where the K constant is about 3 percent larger at the flight Reynolds number compared to at the WT Reynolds number. To quantify the difference between the trends, effects on the integrated aerodynamic forces are summarized in Tables 2 and 3 for microjets with velocity ratio of $U_j/U_\infty = 1.0$ (resulting in $C_\mu \approx 0.005$). It is shown that at the flight Reynolds number, microjet lift enhancement is higher. The higher lift enhancement at the flight Reynolds number is shown to be due to the higher lift enhancement contribution from the outboard flap microjet. Lift enhancement contribution from the inboard flap microjet is the same at both Reynolds numbers.

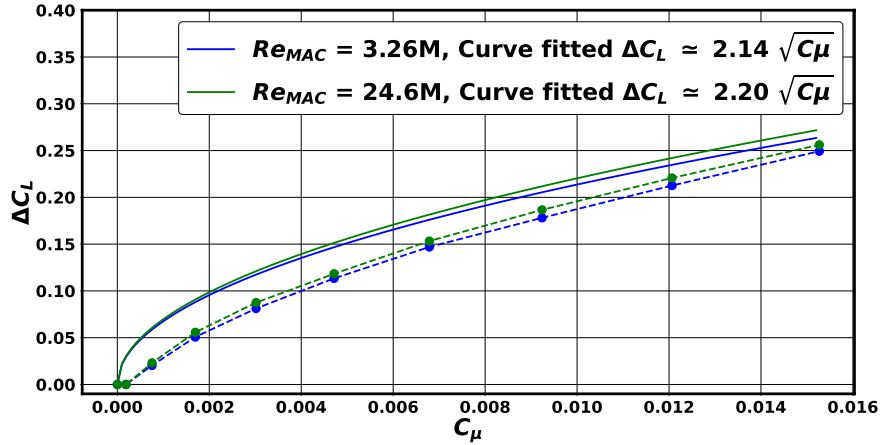


Fig. 9 Comparison of microjet-induced lift enhancement between WT and flight Reynolds numbers at $\alpha = 8.0^\circ$ and $M_\infty = 0.20$. Microjets are implemented on both inboard and outboard flaps on the pressure-side at 95% of flap chord. Dashed lines represent the computational results, while the solid lines represent the trends fit by $K\sqrt{C_\mu}$.

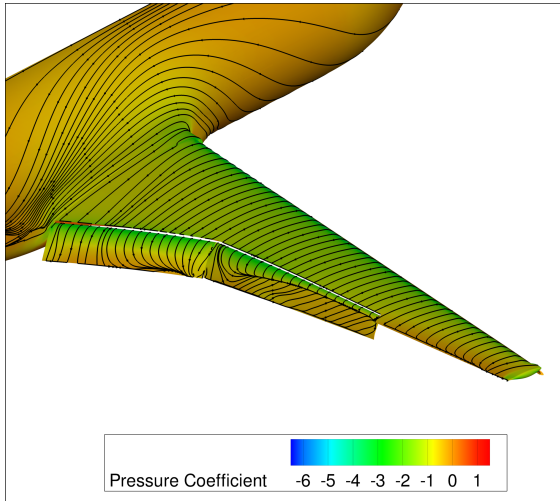
The baseline configuration flow visualisations depicted in Figure 7 show that at both Reynolds numbers the flow separation line on the upper surface of the outboard flap is close to the flap leading edge. Figure 10 depicts microjet effects on these flow features. The highly separated flow on the upper surface of the outboard flap limits the outboard flap microjet's capability to entrain the flow around the trailing edge and thus provide circulation control. Compare this to the microjet effect on the inboard flap with a moderate upper surface trailing edge flow separation at both Reynolds numbers. Microjet-induced lift enhancement on the outboard flap is shown to be approximately half that of the inboard flap. There is a 17% increase in outboard flap microjet lift enhancement at the flight Reynolds number, which can be attributed to less trailing edge flow separation. As depicted in Figure 7, the onset of flow separation is shifted downstream by approximately 5-10% of flap chord on the baseline outboard flap at flight Reynolds number compared to that of the WT Reynolds number. This highlights the sensitivity of microjet performance to the flow features of the configuration it is implemented on.

Table 2 Microjet effect on the aerodynamic forces at flight and WT Reynolds numbers. Microjets are activated across both flaps on the lower surface at 95% flap chord with jet velocity ratio of unity.

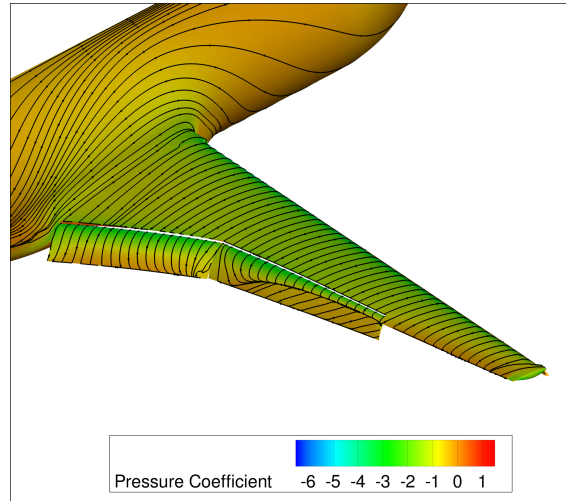
Reynolds number	Baseline C_L	Baseline C_D	+Microjet C_L	+Microjet C_D	ΔC_L	ΔC_D
$Re_{MAC} = 3.26 \times 10^6$	1.752	0.1698	1.866	0.1903	0.114	0.0206
$Re_{MAC} = 24.6 \times 10^6$	1.815	0.1706	1.935	0.1927	0.120	0.0221

Table 3 Decomposition of the integrated aerodynamic forces. Microjets are activated across both flaps on the lower surface at 95% flap chord with jet velocity ratio of unity.

Reynolds number	Baseline C_L	+Microjet C_L	Inboard Microjet ΔC_L	Outboard Microjet ΔC_L
$Re_{MAC} = 3.26 \times 10^6$	1.752	1.866	0.079	0.035
$Re_{MAC} = 24.6 \times 10^6$	1.815	1.935	0.079	0.041



(a) Surface pressure contour at $Re_{MAC} = 3.26M$.



(b) Surface pressure contour at $Re_{MAC} = 24.6M$.

Fig. 10 Comparison of surface pressure contours at flight and WT Reynolds numbers at $\alpha = 8.0^\circ$ and $M_\infty = 0.20$. Microjets are implemented on both inboard and outboard flaps on the pressure-side at 95% of flap chord with $C_\mu = 0.005$.

Comparing Figure 10 with Figure 7 shows that microjets in addition to enabling effective circulation control, also offer separation mitigation in the presence of moderate TE flow separation. Because the TE flow separation is moderate on the baseline inboard flap at both Reynolds numbers, inboard flap microjet lift enhancement is unchanged between the Reynolds numbers as shown in Table 3 and Figure 11. Once microjets are implemented on both inboard and outboard flaps, the overall lift enhancement at the flight Reynolds number at $C_\mu = 0.005$ is about 5% higher and therefore the associated induced drag is higher compared to the WT Reynolds number. Since the outboard flap microjet is not an effective circulation control approach, the applied microjet input C_μ on it is not utilized efficiently. In a scenario where the baseline outboard flaps did not have highly separated trailing edge flow, a given C_μ would likely provide similar lift enhancement on the outboard flap compared to the inboard flap. In such a case additional $\Delta C_L = 0.03$ coming from the outboard flap microjet would recover the square root relationship for the overall lift enhancement as shown in Figure 12. This suggests that $\Delta C_L = K\sqrt{C_\mu}$ relationship would hold more accurately if microjet is implemented on configurations

with moderate flow separation such that microjet activation is effectively utilized for circulation control. Because the inboard flap microjet is shown to be more effective compared to the outboard flap microjet, the remaining investigations consider microjets only on the inboard flap.

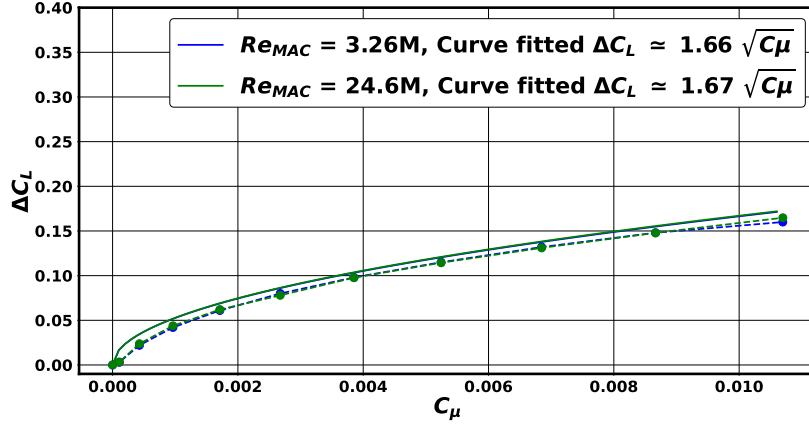


Fig. 11 Comparison of microjet induced lift enhancement between WT and flight Reynolds numbers at $\alpha = 8.0^\circ$ and $M_\infty = 0.20$. Microjet is implemented on the inboard flap only on the pressure-side at 95% of flap chord. Dashed lines represent the computational results, while the solid lines represent the trends fit by $K\sqrt{C_\mu}$.

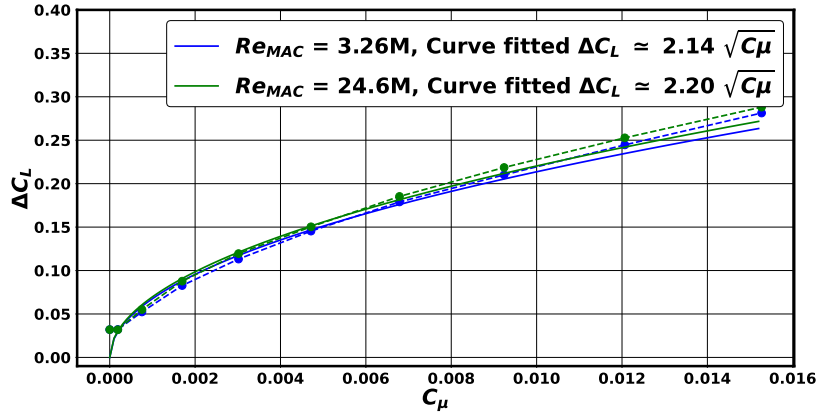


Fig. 12 Comparison of microjet-induced lift enhancements assuming less TE flow separation on the baseline outboard flap at $\alpha = 8.0^\circ$ and $M_\infty = 0.20$. Microjets are implemented on both inboard and outboard flaps on the pressure-side at 95% of flap chord. Dashed lines represent the adjusted computational results, while the solid lines represent the trends fit by $K\sqrt{C_\mu}$.

D. Microjet Effect on the Lift Curve

To investigate whether the microjet on the inboard flap shows any sensitivity to Reynolds number, an angle of attack study employing a microjet with velocity ratio of $U_{jet}/U_\infty = 1.0$ was performed with increments of two degrees. Figure 13 shows that utilizing a microjet with $U_j/U_\infty = 1.0$ (resulting in $C_\mu \approx 0.003$) can shift the linear region of the lift curve by $\Delta C_L = 0.08$ consistently at both Reynolds numbers. Microjet lift enhancement at both Reynolds numbers is found to be primarily due to the increase in pressure lift. The lift generated by microjet's added momentum is only about 2% of the lift generated by the altered pressure field. The microjet's capability in shifting the lift curve in the linear regime (lift enhancement at a given angle of attack) is the primary application for microjets addressing one of the main challenges of designing high-lift systems for commercial airplanes; controlling the pitch attitude angle of the airplane and thereby reducing the likelihood of tail strike. This microjet-induced shift in the lift curve of approximately

$\Delta C_L = 0.08$ shown for relatively small C_μ can potentially lead to major performance improvements and weight savings as explained by Meredith [1].

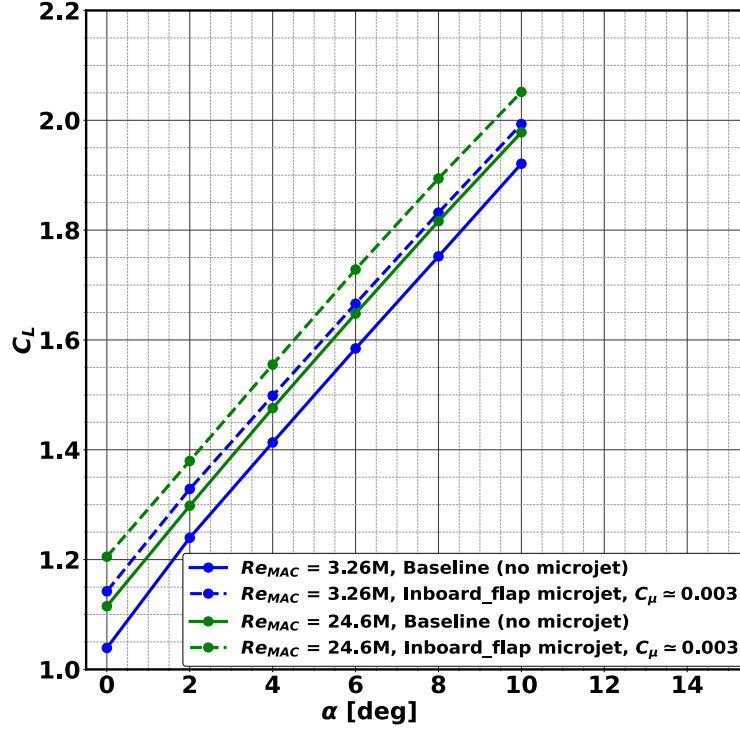


Fig. 13 Reynolds number sensitivity of microjet effect on the lift curve. Microjet is implemented on the inboard flap only with $U_{jet}/U_\infty = 1.0$.

E. Microjet Effect on Aircraft Oswald Efficiency

AFC research focuses on technologies for lift enhancement and often the effects on drag are overlooked. However, recent, related work has put emphasis on the importance of understanding the effects not only on lift but also on drag through performing detailed drag decomposition and lift-to-drag ratio analyses [8, 12, 13]. These analyses provide important insights towards assessing the total system impact of microjets and comparing it against alternative lift enhancement/control approaches (e.g., number of flap elements, flap chord, flap deflection, etc).

The question considered in this section is how the drag penalty of microjet's lift enhancement compares with that of other lift enhancement technologies. One approach to answer this question is to start from a given baseline configuration and attempt to obtain a certain lift enhancement target using various lift enhancement technologies in order to compare the associated drag penalties. Unfortunately, data from alternative lift enhancement methods are usually not available and this approach can become an involved exercise where a majority of the research effort would be put towards generating various lift enhancement configurations rather than addressing the corresponding drag penalties. An intermediate approach is to utilize a global representative design parameter containing information on both lift and drag across the configuration's drag polar. One such parameter is the Oswald efficiency which captures the efficiency of a configuration in generating lift.

For airplanes with significant wing camber, Equation 2 provides the parabolic relationship between drag and lift. Equation 2 can be expanded further to Equation 3. Here, $C_{D_{min}}$ is the minimum drag coefficient containing most of the viscous drag (skin friction and form drag) and some of the induced drag. The second term on the righthand side of Equation 2 represents the drag due to lift component containing most of the induced drag and some of the viscous drag where $C_{L_{min}}$ is the lift coefficient at $C_{D_{min}}$, $AR = b^2/S$ is the wing aspect ratio, and e is the Oswald efficiency factor accounting for the deviation in the spanwise load distribution from the elliptical loading (induced drag efficiency) and for the change in viscous drag due to lift.

$$C_D = C_{D_{min}} + \frac{(C_L - C_{L_{min}})^2}{\pi e AR} \quad (2)$$

$$C_D = (C_{D_{min}} + \frac{C_{L_{min}}^2}{\pi e AR}) + (\frac{-2C_{L_{min}}}{\pi e AR})C_L + (\frac{1}{\pi e AR})C_L^2 \quad (3)$$

A least-square curve fit for the parabolic relationship using equation $C_D = a_0 + a_1 C_L + a_2 C_L^2$ can be used to obtain coefficients a_0 , a_1 , and a_2 . The definitions of these coefficients in Equation 3 results in a system of equations that can be used to solve for Oswald efficiency. Using the high-lift CRM computational drag polar for the baseline configuration and for the configuration with the microjet shown in Figure 14, microjet's effect is shown calculated effect on Oswald efficiency at both Reynolds numbers is shown in Table 4. The lift-to-drag ratio is reduced on account of changes in the spanwise load distribution as a result of microjet activation (Note, in this study the focus is on lift enhancement. Modifying the spanwise load distribution through microjets to e.g. reduce induced drag could be the focus of a future study). The results in Table 4 show an increase in the Oswald efficiency by 2.5% and 5.4% at flight and WT Reynolds number, respectively. The difference in Oswald efficiency increase is likely related to the reduced flow separation on the flaps at the flight Reynolds number and, hence, reduced increase in Oswald efficiency. Future studies will attempt to compare microjets with various lift enhancement technologies (such as employing deeper flap deflections) in terms of the corresponding effects on Oswald efficiency.

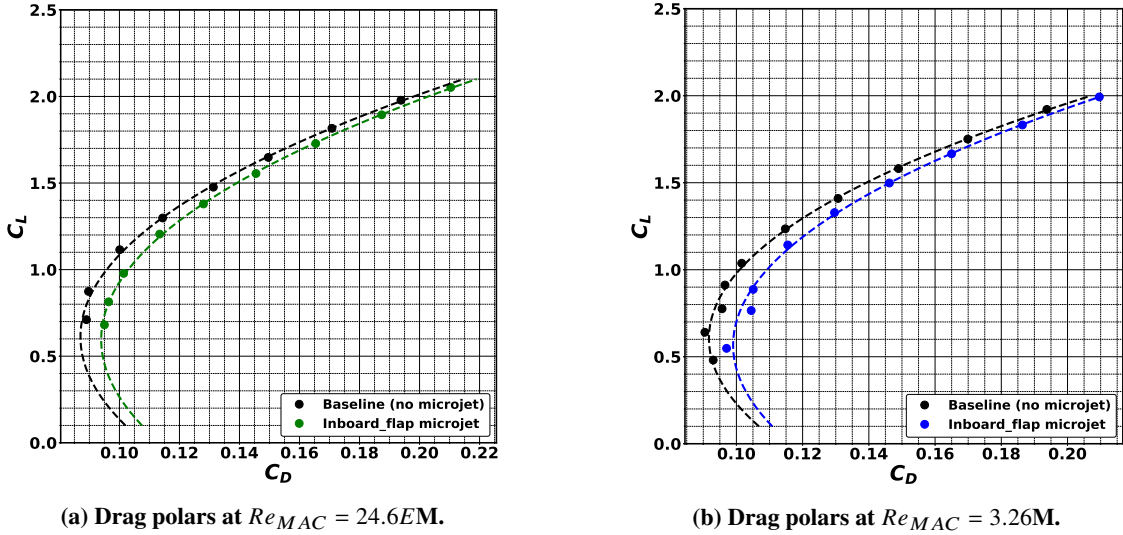


Fig. 14 Drag polar for the configuration without and with a microjet ($C_\mu = 0.003$) embedded on the lower surface of the inboard flap. $M_\infty = 0.20$. Filled circles represent the data and dashed lines represent the parabolic curve fits.

Table 4 Microjet effect on the aerodynamic forces at flight and WT Reynolds numbers.

	C_L	C_D	C_L/C_D	$\Delta(C_L/C_D)$	e	Δe
$Re_{MAC} = 24.6 \times 10^6$						
Baseline	1.815	0.1706	10.64	-	61.5%	-
Inboard-flap microjet	1.894	0.1874	10.11	-0.53	64.0%	+2.5%
$Re_{MAC} = 3.26 \times 10^6$						
Baseline	1.752	0.1698	10.32	-	59.7%	-
Inboard-flap microjet	1.832	0.1864	9.82	-0.50	65.1%	+5.4%

F. Microjet Effect on Trim Drag

With microjet-induced lift enhancement, aircraft trim conditions are affected. To trim an aircraft for higher lift coefficient on the wing, the aerodynamic forces on the horizontal stabilizer must be adjusted so that the aircraft maintains the set attitude. For a conventional aircraft such as HiLiftPW-3, increasing lift coefficient on the wing at a given angle of attack increases the nose down pitching moment as depicted in Figure 15. To offset this change in the pitching moment, the elevators and rimmable horizontal stabilizers must adjust to generate more negative lift which increases the associated trim drag. This section considers how microjet-induced lift enhancement affects the aircraft trim drag. To answer this question, the necessary lift coefficient on the horizontal tail ($C_{L_{trim}}$) is calculated using Equation 4, where $C_{L_{tailoff}}$ is the lift coefficient of the configuration with no tail, $C_{M_{tailoff}}$ is the pitching moment of the configuration with no tail, $X_{tail-MAC}$ and $Z_{tail-MAC}$ correspond to the location of the tail mean aerodynamic center, and X_{cg} and Z_{cg} correspond to the location of the center of gravity.

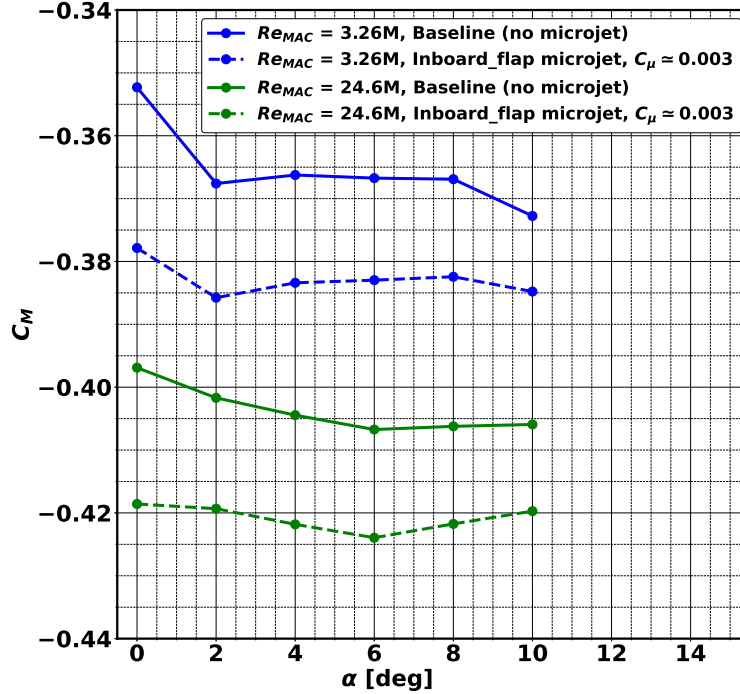


Fig. 15 Reynolds number sensitivity of microjet effect on the pitching moment curve. Microjet is implemented on the inboard flap only with $U_{jet}/U_{\infty} = 1.0$.

$$C_{L_{trim}} = C_{L_{tailoff}} + C_{M_{tailoff}} \frac{MAC}{\cos(\alpha)(X_{tail-MAC} - X_{cg}) + \sin(\alpha)(Z_{tail-MAC} - Z_{cg})} \quad (4)$$

Because the HiLiftPW-3 configuration used in this paper does not include an empennage, the location of the horizontal tail mean aerodynamic center is adapted from the drag prediction workshop configuration [14]. Utilizing the lift, drag and pitching moment data from Figures 5, 14 and 15, trim drag analysis was performed for the range of angles of attack with three assumptions: (1) the drag polar of the tail-off configuration is unchanged from the drag polar of the airplane with tail, (2) the vertical gap between the wing and the horizontal tail is small, and (3) the horizontal tail has negligible effect on the spanwise lift distribution in the Trefftz plane.

Microjet effect on trim drag was found to be consistent throughout all the studied angles of attack. Table 5 shows one angle of attack as an example for this analysis. It is shown that with microjet-induced lift enhancement, the increase in trim drag is about 8 and 13 drag counts at $Re_{MAC} = 3.26$ million and $Re_{MAC} = 24.6$ million. The change in the trim drag is about 0.3% and 0.6% of the total drag which suggests that microjet effect on trim drag is relatively small.

Table 5 Microjet effect on trim drag at $\alpha = 8.0^\circ$ and $M_\infty = 0.2$.

	$C_{D_{pre-trim}}$	$C_{D_{trim}}$	$C_{D_{total}}$	$\Delta C_{D_{trim}}$
$Re_{MAC} = 24.6 \times 10^6$				
Baseline	0.1706	0.0173	0.1879	-
Inboard-flap microjet	0.1874	0.0186	0.2060	0.0013
$Re_{MAC} = 3.26 \times 10^6$				
Baseline	0.1698	0.0153	0.1851	-
Inboard-flap microjet	0.1864	0.0161	0.2025	0.0008

IV. Conclusions

This paper explores the sensitivity of microjet performance to Reynolds number on the high-lift version of the Common Research Model wing/body configuration from the 3rd AIAA CFD High-Lift Prediction Workshop. Flow features on the baseline high-lift CRM configuration prior to microjet activation were initially studied at both a wind tunnel (WT) Reynolds number of $Re_{MAC} = 3.26$ million and a representative flight Reynolds number of $Re_{MAC} = 24.6$ million. It was shown that flow features such as trailing edge (TE) flow separation on both inboard and outboard flaps have noticeable sensitivity to Reynolds number. At the flight Reynolds number, the onset of TE flow separation shifts downstream resulting in less flow separation compared to at the WT Reynolds number. To investigate the sensitivity of microjet effectiveness to Reynolds number, three studies were performed: (1) microjet's lift enhancement relationship of $\Delta C_L = K\sqrt{C_\mu}$, (2) microjet's lift enhancement capability in the linear regime of the lift curve, and (3) microjet's impact on airplane drag characteristics. For the lift enhancement relationship study, microjets were implemented on both flaps and it was found that the K constant in the microjet lift enhancement relationship of $\Delta C_L = K\sqrt{C_\mu}$ is about three percent larger at the flight Reynolds number compared to at the WT Reynolds number. It was also shown that the square root relationship was not completely preserved with microjet activation on both inboard and outboard flaps, while the relationship held for microjet on the inboard flap only. Through a force decomposition analysis it was shown that due to highly separated flow on the outboard flap, the microjet on it was not as effective. The outboard flap microjet lift coefficient enhancement was about 0.03 lower than the inboard flap microjet lift enhancement. Once, the 0.03 shift was applied to the lift coefficient enhancement curve, the square-root relationship was recovered. This study showed that the $\Delta C_L = K\sqrt{C_\mu}$ relationship would hold if microjet is implemented on configurations with moderate TE flow separation.

Since microjets were found to be more effective on the inboard flap, the microjet on the outboard flap was removed for the remaining studies. Microjet lift enhancement of $\Delta C_L = 0.08$ in the linear regime of the lift curve, for microjet velocity ratio of one, was found to be consistent at both Reynolds numbers. This is because the TE flow separation on the baseline configuration prior to microjet activation was moderate on the inboard flap at both Reynolds numbers. The microjet-induced $\Delta C_L = 0.08$ shown in this paper for a relatively small velocity ratio can enable major performance improvements in terms of airplane weight reductions.

To account for microjet effects on drag while capturing the overall lift-enhancement, an Oswald efficiency analysis was developed in addition to carrying a lift-to-drag analysis. It was shown that although the lift-to-drag ratio is reduced with microjet lift enhancement, the configuration's Oswald efficiency is improved by 5.4% at $Re_{MAC} = 3.26$ million and by 2.5% at $Re_{MAC} = 24.6$ million. Further, microjet impact on the trim drag was evaluated and it was shown that microjet-induced lift enhancement increases the trim drag by only less than one percent of the total drag.

The results presented in this work highlight the potential of microjets for improved performance at high-lift conditions. Throughout this paper it is shown that computational investigations of AFC at appropriate flight conditions in addition to commonly used wind tunnel conditions are encouraged to obtain representative lift enhancement trends. For active flow control methods with a focus on circulation control, such as microjets, reduced TE flow separation at higher Reynolds number is shown to positively impact microjet's effectiveness. Future work will address comparison studies between microjet and various lift enhancement technologies. While the high-lift Common Research Model geometry studied in this paper was in the landing configuration, future work will extend the investigations to the take-off configuration.

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