

Active Separation Control at NASA Langley Research Center: A Tribute to Avraham ‘Avi’ Seifert

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The late Dr. Avraham ‘Avi’ Seifert was a National Research Council (NRC) research associate working on active separation control research from 1996 to 1999 at the NASA Langley Research Center (LaRC). While at LaRC, he led pioneering active flow control (AFC) research on periodic excitation as a means of controlling turbulent boundary layer separation at flight Reynolds numbers. In this paper we pay tribute to Avi by reviewing his LaRC active flow control research that includes the four years he was an NRC research associate and the summers following during which he was a visiting researcher.

Nomenclature

c	airfoil chord
C_μ	combined blowing momentum coefficient (c_μ ; $< c_\mu >$)
c_μ	steady blowing momentum coefficient, $\equiv J/cq$
$< c_\mu >$	unsteady blowing momentum coefficient, $\equiv < J' > /cq$
f	oscillation frequency, Hz
F^+	reduced frequency, $\equiv (fx_{sp})/U_\infty$
h	slot width, mm
J	steady momentum at slot exit, $\equiv \rho h U_j^2$
J'	oscillatory momentum at slot exit, $\equiv \rho h u_j'^2$
q	freestream dynamic pressure, $\equiv 1/2 \rho U_\infty^2$
ρ	density
U_∞	average and fluctuating streamwise velocity
x_{sep}	distance from actuator to trailing edge
$<>$	phase locked values

I. Introduction

Prior to the mid 1990s and the start of separation control using periodic excitation research at NASA LaRC, LaRC researchers had spent the years from the mid 1970s to the mid 1990s performing fundamental research aimed at reducing drag. Bushnell[1] states that the impetus for this research was the increase in jet fuel prices caused by the Arab oil embargo of the 1970s. Riblets, a passive drag reduction technique that alters near wall structures in a turbulent boundary layer, and micro vortex generators were products of this research period. Additionally, laminar flow control and hybrid laminar flow control had been or were being studied by researchers at LaRC in the mid 1990s. Active separation control using periodic excitation for drag reduction and improved aerodynamic performance aligned well with these research efforts. Around this time, NASA established the Aircraft Morphing program tasked with developing smart aircraft systems [2]. A multidisciplinary approach that included structures, materials, sensor technology, and flow control was used to develop technologies that would enable future smart aircraft configurations. The active separation using periodic excitation research that is the topic of this paper was an investment area of the NASA Aircraft Morphing program and subsequent programs. Review papers [3–5] describe research activities that included structures and materials research, flow control actuator development, and experimental investigations of separation, circulation, and cavity flow control.

In the mid 1990s NASA LaRC teamed with researchers from Tel-Aviv University (TAU) to examine the effect of Reynolds number on active separation when using periodic excitation. Prior studies on airfoils by Seifert et al. [6] had shown that periodic excitation was both effective and efficient at controlling separation. In this separation control

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technique, periodic excitation is introduced tangential to the surface and upstream of the natural separation location. Reduced frequencies (F^+) of the periodic excitation were found to be optimal when $F^+ \approx 1$. Reduced frequency is defined as $F^+ = fx_{sep}/U_\infty$, where f is the excitation frequency, x_{sep} is distance from the excitation slot to the trailing edge, and U_∞ is the freestream velocity. Seifert and his colleagues at TAU showed that spanwise coherent structures introduced into a boundary layer on the verge of separation enhanced mixing between the lower momentum fluid in the separated flow region and the higher momentum flow above. The excitation frequency was selected to leverage the natural instabilities in the flowfield. Experiments by Seifert et al. [6, 7] had been performed in low-speed, atmospheric tunnels where the maximum Reynolds numbers were about one million. While the technique was effective at these relatively low Reynolds numbers, questions were raised about the utility of the separation control technique near flight Reynolds numbers.

In this publication, we focus on the active separation control research performed by Avi Seifert while he was an NRC Research Associate at NASA LaRC. Since this research has been previously published, this paper includes a brief review with references followed by an attempt at connecting some of the original research performed by Seifert to the research done in more recent years at NASA LaRC. The research topics that we will discuss include the high Reynolds number research performed on an NACA 0015 airfoil and a wall mounted hump model and the AFC research that followed these experiments aimed at simplifying a high-lift system.

II. High Reynolds Number Active Separation Control Research using Periodic Excitation

Spanwise-uniform periodic excitation was used to control separation for all of the active separation control experiments performed at high Reynolds numbers. The excitation was introduced into the flow thru narrow, 2D slots that were nearly tangential to the surface. This AFC research involved developing and evaluating actuation concepts as well as integrating these concepts into relevant configurations.

A. Reynolds Number Effect

Avi Seifert's first AFC experiment at LaRC was designed to answer the question of whether periodic excitation could control separation at high Reynolds numbers. The NASA Langley 0.3-meter Transonic Cryogenic Tunnel (TCT), whose test cross section is 0.33 m x 0.33 m, was selected for the experiment because flight Reynolds numbers can be achieved in this small, cryogenic pressurized facility. Additionally, in a cryogenic pressurized tunnel, Reynolds number and Mach number can be varied independently. During the test, the adaptive walls of the 0.3-m TCT were set to slightly diverge to account for the boundary layer growth.

To facilitate comparisons of the flight Reynolds number results to the TAU low Reynolds number results, an NACA 0015 airfoil with a 30% chord trailing edge flap that could be deflected 0° or 20° was built for the testing in a cryogenic environment (Fig. 1). An oscillatory blowing valve (OBV), based on the TAU valve, was designed and fabricated for the test. A vaporizer was installed on top of the tunnel to convert a fraction of the liquid nitrogen (LN_2) supplied to the tunnel to gaseous nitrogen (GN_2). The GN_2 supplied to the OBV produced the periodic excitation used to control flow separation on the model. An excitation slot at 10% chord was used with the flap 0° configuration and one at 70% chord, the flap shoulder, was used with the flap 20° configuration. During the test, periodic excitation was introduced using either the leading edge slot or the flap shoulder slot. Each internal cavity in the model spanned the width of the airfoil. Periodic excitation produced by the OBV was introduced from one side of the model and the opposite side of the model was connected to the tunnel exhaust system. The exhaust side of the tunnel was connected to atmosphere. Therefore, when the tunnel was pressurized, an exhaust side valve could be used to generate steady suction or to bleed the mean flow from the periodic excitation introduced on the oscillatory blowing valve side. Steady blowing was achieved by holding the oscillatory blowing valve in a fixed position and supplying GN_2 with the exhaust valve closed. With this actuator

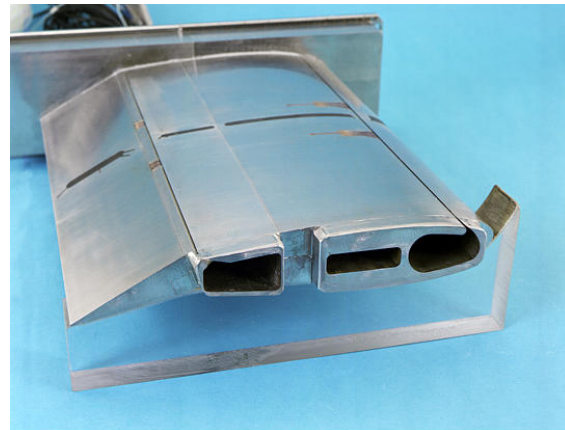
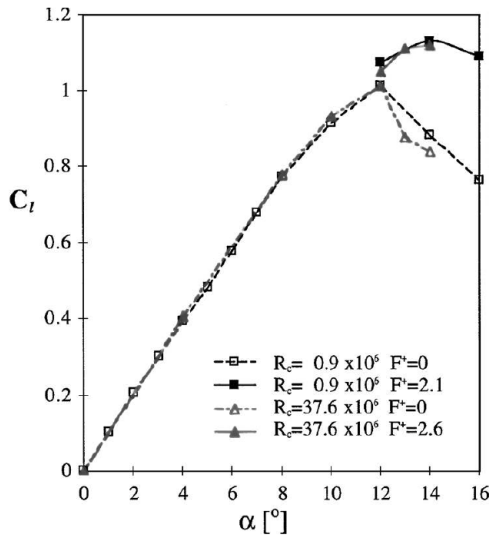


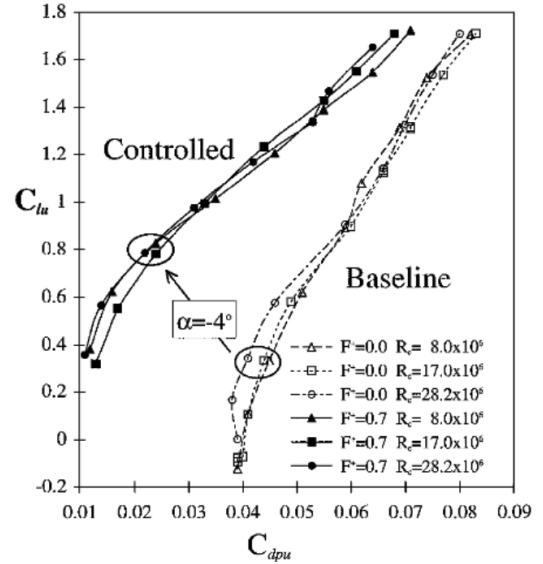
Fig. 1 NACA 0015 active separation control model (Credit: NASA).

arrangement, it was easy to compare the effectiveness of steady mass transfer approaches like steady suction and blowing to periodic excitation with and without a steady component (suction or blowing) superimposed.

Avi Seifert was instrumental in the success of this high Reynolds number AFC wind tunnel experiment where he was involved in all aspects of testing. Experimental results of Ref. [8] show that the increment in C_l from the data acquired at a chord Reynolds number (R_c) near 38 million is similar to that obtained in the TAU experiments at $R_c \approx 1$ million [8] when matching the reduced frequency and momentum coefficient (Fig. 2(a)). The results of Fig. 2(a) were normalized by the maximum lift, $C_{l,max}$, values for the respective Reynolds numbers to aid in the comparison of the results. The coefficient of momentum (C_μ) is a combination of a steady (c_μ) and an unsteady ($\langle c_\mu \rangle$) component usually presented as $C_\mu = (c_\mu; \langle c_\mu \rangle)\%$. The results obtained when control was applied at the flap shoulder with $\delta_f = 20^\circ$ and R_c varying from 8×10^6 to 28×10^6 are shown in Fig. 2(b). The lift versus form drag results of Fig. 2(b) indicate that the lift (C_{lu}) improvement and form drag (C_{dpu}) reduction for a given angle of attack (α) are similar, over the R_c range presented, when F^+ and C_μ are the same. These results answered the question of whether the technique was sensitive to Reynolds number. In agreement with the low Reynolds number TAU results[6, 7], the results from the high Reynolds number experiment on the NACA 0015 airfoil indicated that periodic excitation was effective and more efficient in terms of momentum than steady blowing at controlling separation. When compared to steady blowing, the results of Ref. [8], indicate that periodic excitation using spanwise uniform excitation was as much as two orders of magnitude more efficient in terms of momentum at controlling flow separation on the NACA 0015 with $\delta_f = 20^\circ$. Based on these results, active separation control using periodic excitation was investigated at LaRC in subsequent high Reynolds number experiments.



(a) Comparison of baseline (dashed lines, $F^+ = 0.0$) and controlled (solid lines, $F^+ = 2.1$ and 2.6) flowfields with LE control ($\delta_f = 0^\circ$, $R_c = 0.9 \times 10^6$ and $C_\mu = (0.10; 0.03)\%$ at $M = 0.12$ and $R_c = 37.6 \times 10^6$ and $C_\mu = (0.27; 0.05)\%$ at $M = 0.3$) [8].



(b) Comparison of baseline (dashed lines) and controlled (solid lines) flowfields with TE control ($\delta_f = 20^\circ$, $M = 0.2$, $C_\mu = (0.00; 0.05)\%$) [8].

Fig. 2 High Reynolds number AFC results on NACA 0015.

B. Compressibility and Shock Induced Separation

After answering the question of the effect of Reynolds number on periodic excitation for active separation control at subsonic Mach numbers, the NACA 0015 was used to study separation control using periodic excitation at high Reynolds numbers and compressible speeds [9]. Experiments were performed in the 0.3-m TCT using the NACA 0015 airfoil with $\delta_f = 0^\circ$. Surface static pressures and total and fluctuating pressures from wake surveys were used to assess the effect of periodic excitation on the aerodynamic performance of the airfoil with and without AFC. Unsteady pressure transducers were added at two locations in an existing wake rake to measure the pressure fluctuations in the model wake. Flow separation at compressible speeds usually occurs downstream of the interaction between a shock wave and the boundary layer. The pressure jump across the shock results in a thickening of the boundary layer and a loss of momentum such that separation may occur downstream. Unsteadiness in the shock position and strength downstream of the shock/boundary layer interaction gives rise to a condition known as buffet. During the test in the 0.3-m TCT, excitation from the LE slot located at 10% chord was used to control separation in the compressible flowfield. Periodic excitation produced by the OBV increased lift (Fig. 3), improved L/D, and reduced drag when the excitation slot was close to the separation location [9]. However, unlike the low speed AFC results, oscillatory excitation at compressible speeds was detrimental when placed too far upstream of the separation location [9, 10].

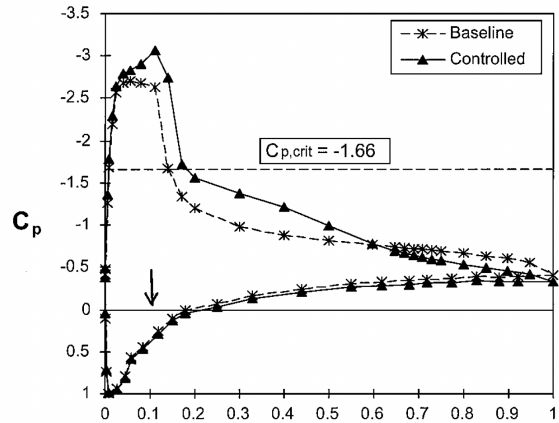
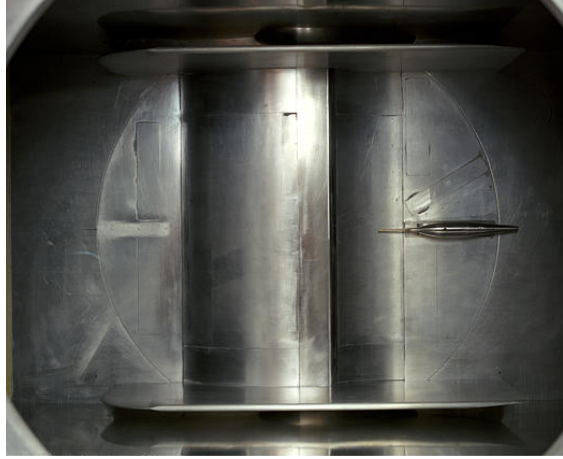


Fig. 3 Baseline and controlled airfoil pressures ($Re_c = 19 \times 10^6$, $M = 0.55$, $F^+ = 1.65$, $\langle c_\mu \rangle = 0.015\%$, $\alpha = 9^\circ$) ([9]).

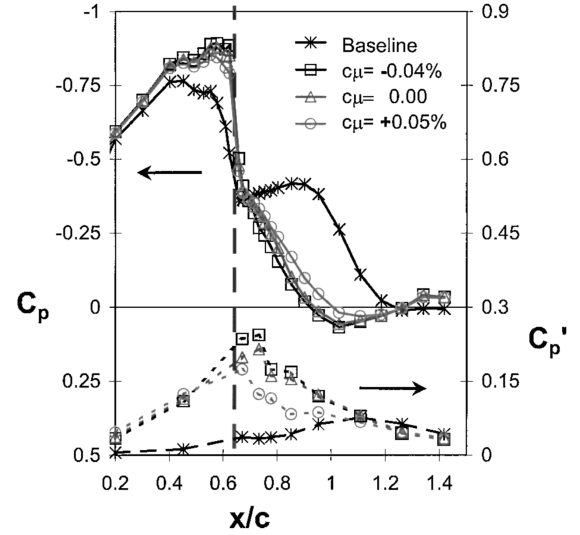
C. High Reynolds Number Wall-Mounted Hump Model

The final high Reynolds number active separation control experiments in the 0.3-m TCT used a generic model configuration designed by Seifert. The "Hump" model, shown in Fig. 4(a), is a 20% thick modified version of the upper surface of a Glauert-Goldschmied type airfoil. Seifert designed the model to help with understanding periodic or oscillatory excitation for controlling separation. It was also designed and tested to generate a dataset that could be used to aid in the development of unsteady computational design tools. Seifert's high Reynolds number "Hump" model was wall mounted and could be tested with and without a 30° sweep angle. The model design included endplates to prevent the sidewall boundary layers from contaminating the flow. Limited optical access in the 0.3-m TCT made the acquisition of off-body measurements challenging. For this reason, Seifert included six slots in the model turntable that could be used to mount a boundary layer probe. Boundary layer surveys were acquired with a Pitot probe that had an integrated unsteady pressure transducer. Due to the cryogenic environment, the probe was installed in a thermally controlled box and attached to a two-axis traverse system allowing the probe to be used to acquire boundary layer profiles at various locations fore and aft of the "Hump" model. This information was acquired to provide inflow conditions. Spanwise uniform periodic excitation, generated by the OBV, could be introduced at either the 59% chord location or closer to the separation location at 64% chord.

Over a series of wind tunnel experiments, a high Reynolds number database was generated for the Hump model. Results from the experimental test campaign can be found in Refs. [11–13]. Parameters investigated included the effects of excitation location, frequency and amplitude, Reynolds number, Mach number, sweep, and steady and unsteady excitation. At incompressible speeds, the excitation slot closest to the natural separation location was the most effective at reattaching the flow [12]. With the ability to control the steady mass flux that accompanied the periodic excitation introduced through the 2D slot, which was 0.5 mm in width, the results indicated that a small amount of suction combined with the periodic excitation was more efficient than periodic excitation alone or periodic excitation with a small amount of steady blowing. This finding is shown in Fig. 4(b) taken from Ref. [11].



(a) Photo of the top of the high Reynolds number Hump model with probe installed (Credit: NASA).



(b) Effect of combining steady and unsteady excitation ($Re_c = 16 \times 10^6$, $M = 0.25$, $\langle c_\mu \rangle = 0.23\%$, $F^+ = 1.5$, $x/c = 0.64$ slot) [11].

Fig. 4 High Reynolds number Hump model.

A low Reynolds number "Hump" model was used as Test Case 3 during CFDVAL2004[14]. CFDVAL2004 was a workshop held in 2004 to assess prediction capabilities of CFD tools when applied to synthetic jets and separation control geometries. The three test cases considered included (1) a synthetic jet in a quiescent environment, (2) a synthetic jet in crossflow, and (3) flow over a hump model. The low Reynolds number Hump model was slightly different geometrically from the high-Reynolds number Hump model. Cost and the optical access provided in a low speed facility drove the selection of a low Reynolds number facility for developing a CFD database for assessing unsteady CFD tools. The experimental database helped the flow control community understand where both experimental techniques and computational tools could be improved. Today, AFC actuator development, flow physics studies [15], measurement test technique evaluation and development like oil film interferometry (OFI) and surface flow vector extraction[16] are performed using the NASA low Reynolds number Hump model as the testbed. The CFDVAL2004 website[14] provides a list of experimental efforts that use the Hump model geometry.

III. Low Reynolds Number Simplified High-Lift

After the successful wind tunnel tests at flight Reynolds numbers using periodic excitation for controlling separation, NASA contracted Boeing to determine where the technology could be implemented on a flight vehicle. The results of the study by McLean et al. [17] prompted a low Reynolds number evaluation of active separation control on a 2D airfoil with simple hinged leading and trailing edge flaps. Testing at low Reynolds numbers was thought to be the correct approach due to the cost of testing in a cryogenic facility and the need to do fundamental experimentation to understand how active separation control could work on a drooped leading edge and how leading and trailing edge excitation should be combined when both the leading and trailing edge control surfaces are deflected as would be the case during takeoff and landing. The Energy Efficient Transport (EET) model was a supercritical airfoil that had been tested with a single element trailing edge flap and a slat. In addition to doing the conceptual design of the simplified high lift (SHL) version of the EET (shown in Fig. 5) that was used for the AFC research, Avi Seifert returned to LaRC for several summers to participate in the testing of the SHL AFC concepts. In total, four low speed tests were performed on the EET model in the Basic Aerodynamics Research Tunnel (BART) to evaluate leading edge (LE), trailing edge (TE), and combined LE and TE flow control.

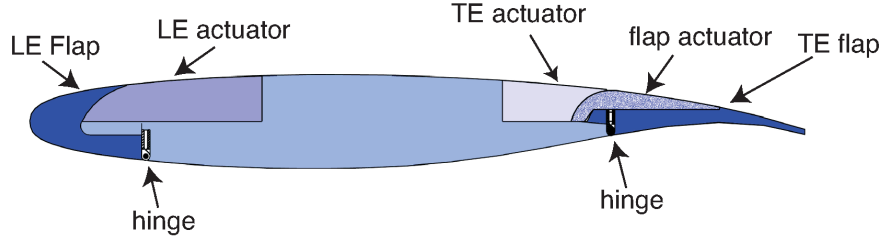
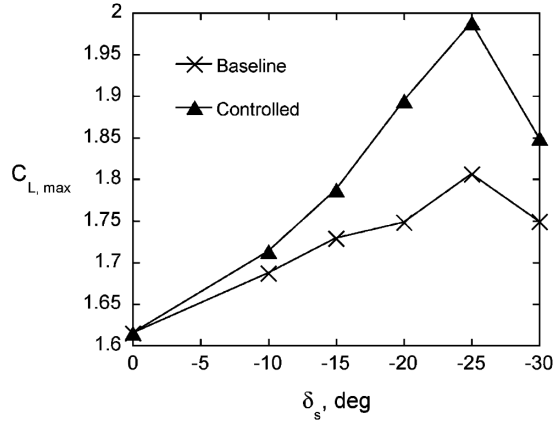


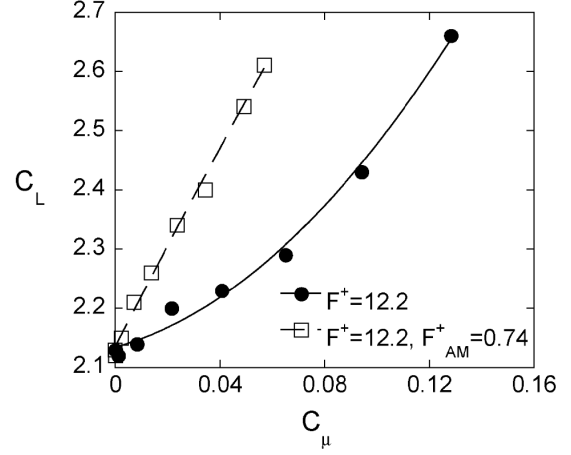
Fig. 5 SHL version of Energy Efficient Transport (EET) with actuator locations highlighted.

A. Leading Edge Control

The simplified high-lift version of the EET had a 406.4 mm chord and a 15% chord leading edge flap with AFC at the LE flap shoulder (Fig. 5). AFC could be introduced nearly tangential to the surface through a 0.88 mm slot located at the shoulder of the LE flap ($x/c = 0.14$) and a 0.5 mm wide slot located at $x/c = 0.3$. No significant benefit was observed from the use of the downstream LE slot during the study [18]. Leading edge control was explored because the Boeing study [17] pointed out that additional research was needed to demonstrate the effectiveness of AFC with a drooped or simple hinge leading edge flap. Piezoelectric actuators were used to generate the zero-net-mass-flux (ZNMF) actuation needed for flow control. Amplitude modulation (AM) was used with these resonance based actuators to produce reduced frequencies (F^+) near one. Since the ZNMF actuator could only produce an unsteady C_μ , the total C_μ is considered to be from the unsteady component and the bracket notation is dropped. Likewise, C_L is used when presenting lift coefficient results computed from surface static pressures. The model was also equipped with hot-films to determine transition and separation locations. The study focused on a model configuration with leading edge flap deflection $\delta_s = -25^\circ$ and trailing edge flap deflection $\delta_f = 30^\circ$ as this was thought to be similar to a landing configuration on a commercial transport. The relationship between $C_{L,max}$ and leading edge flap deflection angle with and without LE AFC is illustrated in Figure 6(a). Deflecting the LE flap to $\delta_s = -25^\circ$ increased $C_{L,max}$ by about 12% and adding periodic excitation to the deflected leading edge flap increased the lift increment by an additional 10% [18]. Frequency scans at a constant C_μ showed that the most effective AM frequencies for reducing drag and increasing lift ranged from $F_{AM}^+ = 0.25$ to 1.25. In Fig. 6(b), the momentum requirements for a given lift increment are compared when driving the piezoelectric actuator with pure sine (PS) wave and when using amplitude modulation to produce ($F_{AM}^+ = 0.75$). The results indicate that a 50% reduction in C_μ is possible when using AM ($F^+ = 12.2$ with $F_{AM}^+ = 0.74$) compared to using PS excitation ($F^+ = 12.2$).



(a) Effect of LE flap deflection with and without AFC on $C_{L,max}$ ($Re_c = 750,000$, $\delta_f = 4.3^\circ$, $C_\mu = 0.03\%$, $F^+ = 14$) [18].



(b) Comparison of PS and AM LE Excitation ($Re_c = 750,000$, $\alpha = 15^\circ$, $\delta_s = -25^\circ$, $\delta_f = 30^\circ$) [18].

Fig. 6 LE AFC on SHL EET Model.

B. Trailing Edge Flap Control

The SHL version of the EET model was built with a 25% chord trailing edge flap (Fig. 5). The model was modular and piezoelectric based zero net mass flux actuators could be installed at the flap shoulder and on the flap. Initial experiments were performed to understand the effect of control emanating from the flap surface. The actuator on the model flap had several slots so that the excitation location could be varied as the flap deflection angle was increased (Fig. 7). During testing with the flap actuator, one slot was used at a time. When a single slot was in use, the remaining slots were filled. The flap deflection (δ_f) range of the model was 0° to 60° to account for the fact that higher flap deflection angles would be needed for a simple hinge flap to achieve the lift increments of a Fowler flap. Controlling separation on the flap of the SHL EET required more momentum than was needed for leading edge separation control on the model.

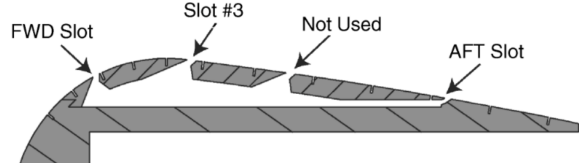
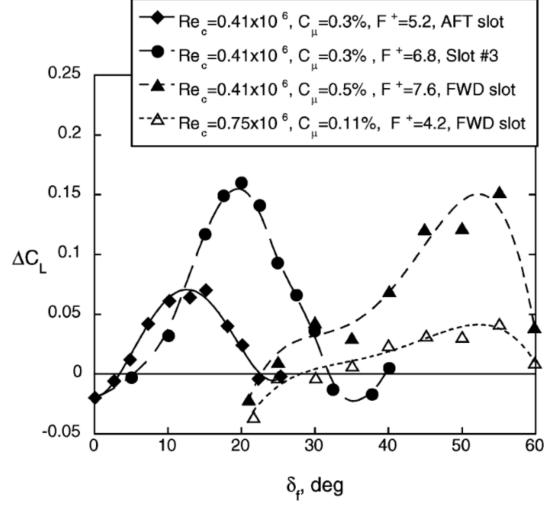


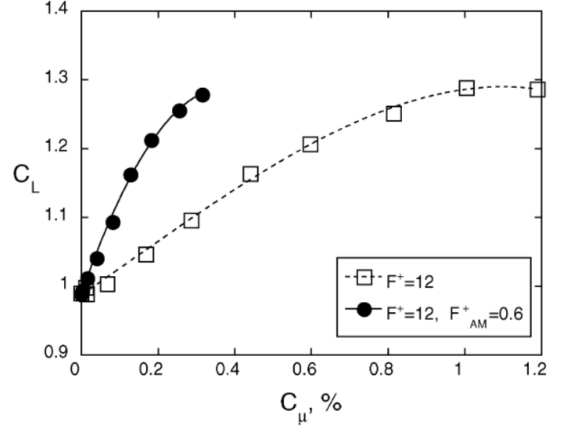
Fig. 7 SHL EET flap actuator cross section [19].

The lift increments obtained when varying the flap excitation location are presented in Fig. 8(a). The aft slot, located at $x/c = 0.845$, when $\delta_f = 0^\circ$, is most effective when $\delta_f \approx 12^\circ$. Slot #3, located approximately 9% chord upstream of the aft slot, is most effective at $\delta_f = 20^\circ$. The FWD slot is exposed to the external flow when $\delta_f > 22^\circ$ and most effective when $\delta_f \approx 50^\circ$. Note that the small difference in slot locations, $x/c \approx 3.2\%$, between the FWD slot and Slot #3, results in a 30-deg change in δ_f for maximum effectiveness of the two slots. For comparison, the difference between the aft slot and Slot #3, $x/c \approx 9\%$, results in only an 8° difference in δ_f for maximum effectiveness. A possible explanation for this finding is that the FWD slot region has surface curvature, whereas the upper TE flap surface, downstream of Slot #3, is almost flat [19].

To improve the momentum efficiency of the flap actuator, AM of the piezoelectric actuator was used to generate a reduced frequency near 1. Amplitude modulation of the high frequency excitation produced by the piezoelectric actuators reduced the C_μ required by a factor of 3 (Fig. 8(b)) [19].



(a) Effect of TE flap excitation location on lift increment as TE flap deflection varied ($\alpha = 0^\circ$, $\delta_s = 0^\circ$) [19].



(b) Comparison of PS and AM TE flap excitation from Slot#3 ($Re_c = 240,000$, $\alpha = 0^\circ$, $\delta_s = -25^\circ$, $\delta_f = 20^\circ$) [19].

Fig. 8 TE flap AFC on SHL EET Model.

Simultaneous actuation upstream and on the flap of the SHL EET model was studied in a separate wind tunnel experiment[20]. During the experiment, piezoelectric actuators were installed upstream of the flap shoulder (TE actuation) and combined with the excitation produced by the flap actuator. For this test, $\delta_f = 20^\circ$ and the leading edge flap was set at $\delta_s = -25^\circ$. The upstream (TE actuator) had a resonance frequency of $f = 1.3$ KHz, and the flap actuator using the third slot (Slot #3) from the trailing edge had a resonance frequency of 1.0 ± 0.3 KHz. Slot #3 of the flap actuator was the optimal slot location for controlling separation on the flap with $\delta_f = 20^\circ$. One of the primary objectives of the experiment was to determine if multiple actuators could be combined to improve the effectiveness of the AFC. The actuators were driven in burst modulation (BM) mode so that the frequency of the two closely spaced actuators could be modulated at the same frequency (f). Burst modulation also had the advantage of allowing the duty cycle (Dcy) to be reduced to potentially further improve the efficiency of the excitation compared to the PS excitation. TE actuation as opposed to actuation on the flap from Slot #3 required more momentum to achieve a similar lift increment. Using the same BM frequency (f_M) and Dcy ≈ 0.3 , the optimal phase angle ϕ for increasing lift was $\pm 30^\circ$ when combining the TE and Slot #3 excitations (Fig. 9) [20].

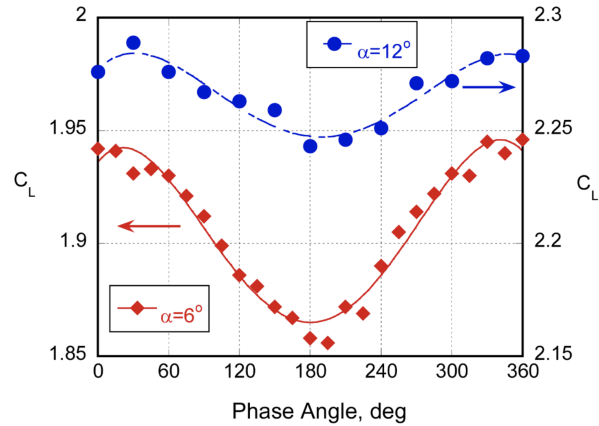


Fig. 9 The effect of phase angle between Slot #3 and the TE actuator ($Re_c = 0.24 \times 10^6$, $F_{M,TE}^+ = 0.52$, $F_{M,slot3}^+ = 0.47$, $f_M = 42$ Hz, $\delta_s = -25^\circ$, $\delta_f = 20^\circ$) [20].

Figure 10 summarizes the lift performance when excitation was introduced from multiple locations on the SHL EET model with $\delta_s = -25^\circ$ and $\delta_f = 20^\circ$. Lift results are presented when controlling flow separation using the individual actuators: LE, TE, and flap (FLP). PS excitation was used with the LE actuator and BM signals with $D_{cy} \approx 0.3$ were used with the TE and FLP actuators. Lift at α values prior to stall is increased when using either the LE, TE, or FLP actuator. FLP excitation using Slot #3 was the most effective at improving the efficiency of the flap, thereby increasing lift prior to stall, when compared to the baseline (uncontrolled) results. LE control produced the largest increment in $C_{L,max}$. In an attempt to increase lift and delay stall, AFC from the LE was combined with AFC from the TE and FLP. For the result presented in Fig. 10, the AFC parameters for the actuators when combined matched those of the individual actuators. AFC using all three actuators (LE+TE+FLP), resulted in an increment in lift before stall that was larger than the lift increment obtained when the actuators were operated individually. However, there was an unexpected and unexplained lift reduction near $C_{L,max}$ requiring further research. Combining excitation from the LE and FLP actuators provided the largest increment in $C_{L,max}$ and delayed stall by 1° when compared to the baseline. For the α range presented, the lift improvements for the combination of the LE and FLP actuators before stall were similar to those obtained with all actuators active (LE+TE+FLP).

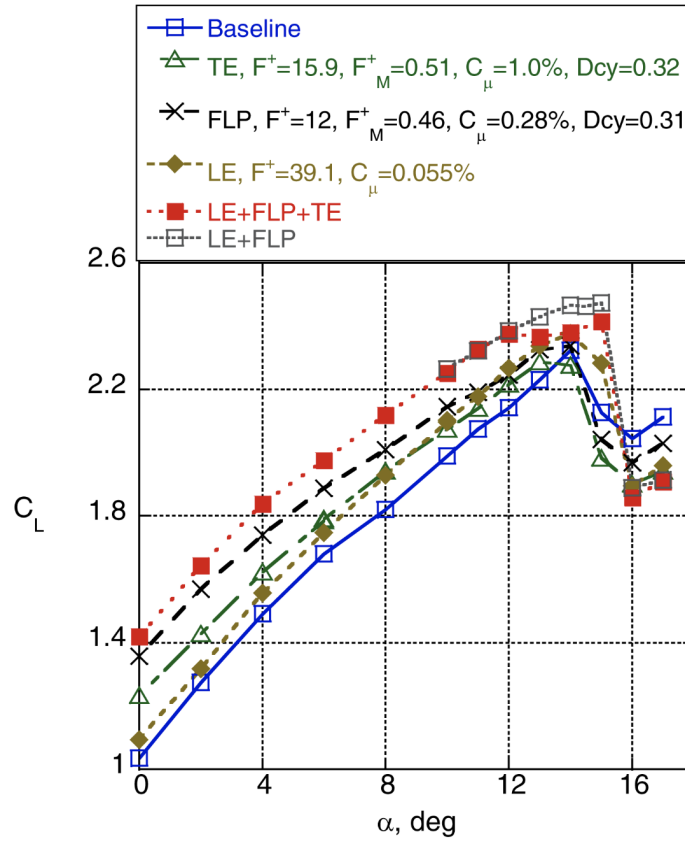


Fig. 10 Lift performance of the SHL EET with LE, TE, and flap Slot #3 AFC ($Re_c = 0.24 \times 10^6$, $\delta_s = -25^\circ$, and $\delta_f = 20^\circ$).

Limitations in the efficiency and effectiveness of ZNMF actuators prevented the application of this type of AFC at flight Reynolds and Mach numbers, for most researchers. Fluidic oscillators like the sweeping jet actuators are often used for this reason. Sweeping jet (SWJ) actuators are discrete jets that produce a spatially oscillating jet due to the internal geometry of the actuators. In contrast to the spanwise uniform excitation produced by the OBV and ZNMF actuators used in the high Reynolds number and EET SHL research, respectively, SWJ actuators produce discrete jets that enhance mixing by the streamwise vortices they produce. The frequency of oscillation of the jet is dependent on the size of the actuator and the input mass flow rate. For a wind tunnel experiment similar in size to the EET SHL airfoil,

these jets oscillate in the KHz range, producing reduced frequencies much higher than 1. Following the successful flight demonstration of active separation where sweeping jet actuators were used during the NASA/Boeing vertical tail flight demonstration[21] to control separation and improve side force, the NASA Advanced Air Transport Technology project funded research to explore the SHL concept on the high-lift version of the Common Research Model (CRM-HL). The CRM-HL model is a relevant, open high-lift geometry defined by Lacy and Sclafani [22]. A 10% scale CRM-HL model was built with interchangeable TE flaps. For the SHL testing of the CRM-HL model, the lift performance of the model with simple hinged inboard and outboard flaps with actuators for controlling flap flow separation was compared to the lift performance of the model with single element inboard and outboard Fowler flaps. Replacing the conventional Fowler flaps with simple-hinged flaps augmented by AFC was shown by Hartwich et al. [23] to reduce fuel burn by up to 2.25%. Due to the complexity of the geometry when compared to a 2D airfoil, pretest CFD simulations were used to select AFC actuators that would enable the CRM-HL with SHL flaps to match the lift performance of the CRM-HL with single element Fowler flaps [24, 25]. The SHL flaps with hinge line actuator cartridges consisting of upstream sweeping jets and downstream steady blowing jets were demonstrated computationally to match the lift performance of the CRM-HL with single element Fowler flaps[24, 25]. These results were later verified in a wind tunnel test campaign[26, 27].

IV. Turbulent Jet Flow Control

Another activity that Avi Seifert engaged in while at LaRC was serving as a graduate advisor on the thesis topic "Periodic Excitation for Jet Vectoring". For this study, a short wide angle diffuser was attached to the exit of a low speed jet. Periodic excitation, produced by piezoelectric actuators, was introduced at the juncture between the jet exit and the diffuser inlet. Excitation could be introduced in either the streamwise or cross stream direction. Excitation amplitude and frequency along with jet diffuser length and half-angle were parameters that were investigated. Excitation introduced in the streamwise direction enhanced mixing and promoted attachment of the jet shear layer to the diffuser wall. Jet vectoring occurred when the streamwise excitation was introduced over a fraction of the circumference of the circular jet. This approach to jet vectoring is similar to flow attachment over a deflected flap when periodic excitation is used to control flow separation. Wave packets were introduced in the jet shear layer with and without the diffuser present. The amplification of the wave packets when the diffuser was attached indicated that the addition of a diffuser significantly amplified the pulsed excitation introduced in the streamwise direction. Excitation introduced in the cross-stream direction pushed the jet away from the diffuser wall.

Excitation from multiple locations was examined in ensuing jet AFC research using the axisymmetric jet [28]. Similar, to the research on the EET SHL airfoil, combining the streamwise and cross-stream excitation resulted in a larger jet deflection angle than could be produced using either the streamwise or cross-stream excitation alone. Following the axisymmetric jet studies, AFC was applied to a rectangular jet [29].

V. Summary

In this paper, we provided a brief review of the active flow control (AFC) research performed by Dr. Avi Seifert from the late 1990s into the early 2000s as part of a partnership between NASA and Tel-Aviv University to explore the efficacy of periodic excitation for controlling boundary layer separation at elevated Reynolds numbers. His research was focused on understanding and demonstrating how to efficiently control separation using unsteady excitation. Avi and his colleagues at Tel-Aviv University had shown in low Reynolds number experiments that separated flow was more receptive when controlled using frequencies that coincided with the natural instabilities in the flowfield. Active separation control is a technology that has been demonstrated to improve aerodynamic efficiency by eliminating or reducing separation. A barrier to widespread use of the technology is the energy requirement of the AFC system. The high Reynolds number experimental results illustrating the momentum efficiency of periodic excitation were compelling and laid the foundation for subsequent investment at NASA in AFC tests at both low and flight Reynolds numbers. The research he performed and documented while at LaRC helped in advancing the technology of periodic or unsteady excitation for separation control. In this paper, written for the special session in memory of Avi Seifert, we have focused on the portion of his career spent at NASA LaRC while recognizing that Avi Seifert made significant AFC contributions prior to and after his time at NASA LaRC.

Acknowledgments

This paper was written for the special AIAA special session "Active Flow Control in honor of Avi Seifert" honoring Dr. Avi Seifert who passed away in October of 2023. I was a researcher in the group at LaRC that Avi joined and had the pleasure and opportunity to work alongside him in performing some very detailed and challenging high Reynolds number cryogenic active flow control experiments followed by testing on a simplified high-lift airfoil. During this period, there was an abundance of flow control research examining the aerodynamic performance of jets and airfoil with and without control, designing robust actuators, and understanding the requirements for open and closed loop flow control systems. Dr. Seifert also suggested the research topic for my Master of Science Degree and provided the guidance to perform the research.

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