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Separation Control at Flight Reynolds Numbers: Lessons Learned and Future Directions

Avi Seifert

Tel-Aviv University, Tel-Aviv, Israel and ICASE, Hampton, VA

and

LaTunia G. Pack

NASA Langley Research Center, Hampton, VA

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Avi Seifert[♦] and LaTunia G. Pack[✦]
NASA Langley Research Center and [♦]Tel-Aviv University

Abstract

Active separation control, using periodic excitation, was studied experimentally at high Reynolds numbers. The effects of compressibility, mild sweep, location of excitation slot and steady momentum transfer on the efficacy of the method were identified. Tests conducted at chord Reynolds numbers as high as 40×10^6 demonstrated that active control using oscillatory flow excitation can effectively delay flow separation from, and reattach separated flow to aerodynamic surfaces at flight conditions.

The effective frequencies generate one to four vortices over the controlled region at all times, regardless of the Reynolds number. The vortices are initially amplified by the separated shear-layer, and after initiating reattachment, the strength of the vortices decay as they are convected downstream. Large amplitude, low frequency vortices break down to smaller ones upon introduction at the excitation slot. The effects of steady mass transfer were compared to those of periodic excitation. It was found that steady blowing is significantly inferior to periodic excitation in terms of performance benefits and that the response to steady blowing is abrupt, and therefore undesirable from a control point of view. Steady suction and periodic excitation are comparable in effectiveness and both exhibit a gradual response to changes in the magnitude of the control input. The combination of weak steady suction and periodic excitation is extremely effective while the addition of steady blowing could be detrimental.

Compressibility effects are weak as long as separation is not caused by a shock-wave/boundary-layer interaction. The undesirable effects of the shock-induced separation could be alleviated by the introduction of periodic excitation upstream of the shock wave, inside the region of supersonic flow.

The effects of mild sweep were also studied and periodic excitation was found to be very effective in reattaching three-dimensional separated flow. Scaling laws that correlate 2D and 3D controlled flows were tested and verified.

Several performance benefits could be gained by applying the method to existing configurations, but it is expected that the full potential of the method can only be realized through the design of new configurations. A comprehensive, fully turbulent, database was generated in order to guide the development, and enable validation, of candidate unsteady CFD design tools.

Nomenclature

a	speed of sound, $\equiv \sqrt{\gamma R T}$
c	airfoil chord
c_μ	steady blowing momentum coefficient, $\equiv J/cq$
$\langle c_\mu \rangle$	oscillatory blowing momentum coefficient, $\equiv h/c\left(1 + T_\infty / T_j\right)\left(\langle u' \rangle / U_\infty\right)^2$
C_μ	combined blowing momentum coefficient, $\equiv (c_\mu; \langle c_\mu \rangle)$
C_m	moment coefficient
C_n	normal force coefficient
C_p	wall pressure coefficient, $\equiv (P - P_S)/q$
C_{pt}	total pressure coefficient, $\equiv (P_t - P_s)/q$
C_d	total drag coefficient
C_{dp}	form drag coefficient
C_l	lift coefficient
C_p	pressure coefficient, $\equiv (P - P_s)/q$
C_p'	fluctuating pressure coefficient, $\equiv p'/q$
f	frequency [Hz]
F^+	reduced frequency, $\equiv f x_{te} / U_\infty$
F_b^+	reduced frequency, $\equiv f x_b / U_\infty$
GN_2	gaseous nitrogen
h	slot height or width
J	momentum at slot exit, $\equiv \rho h U_j^2$

[♦] Senior lecturer, Dep. of Fluid Mech. and Heat Transfer, Faculty of Eng, Tel-Aviv Uni., Ramat-Aviv, 69978, Israel. Seifert@eng.tau.ac.il, Also: visiting scientist, ICASE, NASA LaRC. Senior member, AIAA.

[✦] Reasearch engineer, Flow Physics and Control Branch, MS 170, NASA Langley Research Center, Hampton, VA 23681. L.g.pack@larc.nasa.gov.

LN_2	liquid nitrogen
M	Mach number, $\equiv U_\infty / a$
P	pressure
q	free stream dynamic pressure, $\equiv 1/2 \rho U_\infty^2$
R_c	chord Reynolds number, $\equiv U_\infty c / \nu$
T	temperature
U, u	averaged and fluctuating velocity
W.U.	Wake unsteadiness, $\frac{1}{qc} \int_{-\infty}^{\infty} p_w' dY$
X_b	bubble legnth
x/c	normalized streamwise location
x_{te}	distance from actuator to TE
Y/c	distance normal to airfoil surface
z	spanwise location
α	airfoil angle of attack, deg
Λ	sweep angle, deg
Δ	difference between baseline and controlled parameter
ν	kinematic viscosity
ρ	density

Abbreviations

BLC	boundary layer control
CFD	computational fluid dynamics
LE	leading edge
TE	trailing edge
< >	phase locked values

Subscripts

bt	bench-top
c	condition at model cavity
crit	critical Mach number
cryo	cryogenic conditions
d	de-rectified hot-wire data
R	reattachment
ref	tunnel static conditions
s	tunnel static conditions
sp	separation
std	steady
t	tunnel total conditions
wt	wind tunnel
∞	free-stream conditions
j	conditions at blowing slot
max	conditions at maximum lift
u	uncorrected
w	wake
2D	two dimensional
3D	three dimensional

Superscripts

′	root mean square of fluctuating value

1. Introduction

1.1 Overview

Active Flow Control (AFC) is an engineering discipline that deals with altering a natural flow pattern from taking an undesired path. It was preceded by Boundary Layer Control (BLC) research that dates back to the turn of the 20th century (e.g. Prandtl, in Ref. 1). Boundary layer separation and its control are of particular interest, due to the detrimental effects boundary layer separation has in limiting the performance of flow related machinery and eluding analysis. Despite a significant body of successful research, low efficiency, complexity and maintenance difficulties prevented the utilization of laboratory proven BLC techniques, such as blowing or suction. Forced oscillations superposed on a mean flow that is on the verge of separating proved to be very effective in delaying turbulent boundary layer separation[2]. The delay of boundary-layer separation increases the useful angle of attack range of airfoils and flap deflection angles. It also increases the circulation around the entire configuration. Oscillatory flow excitation is significantly more effective than steady, tangential blowing for separation control[3-6], because the steady wall-jet utilizes added momentum alone to overcome the adverse pressure gradient. This paper includes a detailed comparison to the effects of steady suction as well.

1.2 High Reynolds numbers

It has been hypothesized that unsteady separation control, especially with laminar separation, is similar to active boundary layer tripping because both methods take advantage of an instability mechanism. To eliminate this hypothesis, transition strips were located at the leading edge (LE) region of airfoils and generic flap configurations[2-4]. It was shown that forced transition, thickened turbulent boundary layers and elevated Reynolds numbers (up to 3.3 x 10^6 tested previously[7]) did not reduce the efficiency of the method. Moreover, as the R_c increases, the tendency of the boundary layer to separate decreases because of the relative increase in inertia forces with respect to viscous forces (expressed also as the relative decrease between the momentum thickness at the separation location and the airfoil chord). Still, a high-Reynolds-number demonstration was missing. The initial purpose of the investigation was to increase the upper limit of R_c tested and to demonstrate the effectiveness of periodic excitation for separation control at high R_c[5].

1.3 Compressible speeds

Flow separation at compressible speeds typically occurs downstream of a shock-wave boundary-layer interaction. The pressure jump across the shock either causes immediate separation or thickens the boundary layer and reduces its momentum such that it separates further downstream. Once the flow separates downstream of the shock, the unsteady separation and subsequent reattachment (if it occurs) induce unsteadiness in both the shock position and strength. This phenomenon is known as buffeting. These low frequency oscillations can cause structural damage, if coupled with the resonance frequencies of the structure. Porous strips and wall bumps[8, 9] are effective in reducing the strength of the shock wave and hence delay buffet onset. Vortex generators (mechanical[10, 11] or canted jets[12]) as well as suction through slots are effective at controlling shock-induced separation and alleviating buffet. Bump position, height and shape are tailored to a specific flow condition. Porous strips cover about 10% of the chord, cause transition on laminar airfoils and increase skin friction drag. Porosity and slot locations are also mission tailored. While these devices could be designed to widen the flight envelope to a certain extent, their application for guidance and control, which requires fast response[13] is doubtful. To maximize efficiency, these methods need to be actively controlled. Furthermore, efficiency considerations rule out the use of tangential blowing and stealth considerations rule out the use of mechanical vortex generators. Therefore, fast responding, active methods for management of compressible unsteady flows were studied.

1.4 The need for a design tool

Though demonstrated experimentally, active separation control at high Reynolds number and compressible flows using periodic excitation, is still a challenge for theoretical and numerical analysis, and consequently design tools are not available. The appropriate use of active BLC should enable simplified, cheaper, more efficient and reliable systems, while maintaining performance. A multi-disciplinary design optimization process should allow simplified high-lift systems, thicker airfoils that will allow lighter structures and greater internal volume, shorter aft bodies, size reduction and even elimination of conventional control surfaces. Existing design tools are capable of simulating steady flows, including steady mass transfer. However, the inclusion of unsteady BLC effects into CFD tools has not been performed. The development of a proper CFD design tool is dependent on the availability of a comprehensive database at relevant conditions (i.e. flight Reynolds numbers), to allow its validation. Therefore, an experiment was designed with the aim of improving our understanding of controlling separated flows at flight Reynolds numbers and providing a comprehensive database for validation of unsteady CFD design tools[14]. Specifically, the effects of compressibility, sweep and location for introduction of the control input were explored. The "Hump" experiment is also intended to supplement the airfoil experiments by providing additional flexibility in the control parameters and more detailed measurements of the mean and fluctuating wall pressures as well as boundary layers. The flow over the model was fully turbulent so Laminar-turbulent transition was not an issue and the tunnel wall interference was reduced.

1.5 Effects of Sweep

Sweep and compressibility are associated in the sense that sweep was initially introduced in order to reduce the effective wing thickness ratio and therefore delay the appearance of shock waves to higher free-stream Mach numbers. The importance of separation control over 3D configurations stems from the need to optimize high lift systems of swept wing airplanes as well as other 3D flows. While 2D flow is relatively simple to establish and analyze, quasi "2D" swept flow or "infinitely swept" flow is extremely complicated to establish and is even more challenging in the presence of separation. We have studied the effects of active separation control by rotating the "Hump" model to a mild sweep angle of 30 deg and comparing the results to those obtained in the absence of sweep.

1.6 Scope and layout

This investigation and resulting publications do not claim to provide a comprehensive description of the flow field dynamics, as this could not be provided by only measuring the wall pressures and a limited number of velocity profiles. Rather it attempts to deepen the understanding of several key features and provide validation cases for future CFD. A brief review of the experimental set-up is provided in Sec. 2. A narrative description of the effects of the leading parameters that include the Reynolds number, excitation frequency and its magnitude, compressibility, sweep, boundary layer thickness and excitation slot location are provided in Sec. 3. Conclusions are provided in Sec. 4 and Recommendations are given in Sec. 5.

2. Description of the Experiments

2.1 Overview

The experiments were conducted in a pressurized cryogenic wind tunnel, which has advantages and disadvantages for active flow control investigation. For example, a cryogenic pressurized facility allows independent control of R_c and M at a fixed free-stream velocity. With this type of control, the effective frequencies are easily found because F^+ can be held fixed while R_c is varied and M is invariant. Another advantage of testing in a cryogenic pressurized facility is the ability to generate a zero-mass-flux disturbance when using a pulsed injection valve. It was possible to exhaust all of the mass flux introduced by the oscillatory valve simply by venting the model cavity, using the pressure difference between the wind tunnel and the exhaust side of the model. One of the disadvantages of testing in a cryogenic pressurised facility is that an in situ determination of $<c_\mu>$ is very difficult. However, using atmospheric bench-top tests and a simplified flow model, it is possible to estimate the magnitude of $<c_\mu>$ that was used[5] in the wind tunnel.

This section contains only a brief description of the experiments. A more detailed description can be found in Refs. 5 and 14. Tests were conducted on two configurations of a NACA 0015 airfoil and on a wall mounted model (the "Hump").

2.2 The 0.3-m Transonic Cryogenic Wind Tunnel

The experiments were conducted in the 0.3-m Transonic Cryogenic Tunnel at the NASA Langley Research center. It is a closed-loop, fan-driven tunnel with a test cross section of 0.33 x 0.33 m^2. Gaseous nitrogen is the test medium. The tunnel operates at stagnation pressures ranging from 1.2 bar up to 6 bar and total temperatures from 78 K up to 327 K[15, 16]. The floor and ceiling of the tunnel were diverged in the vicinity of the models to reduce blockage resulting from boundary-layer growth on the test section walls. A wake rake of total pressure probes was located 2.2 chord lengths down-stream of the airfoil mid-chord[15]. Two of the total pressure probes in the wake rake were instrumented with dynamic pressure transducers in order to measure the wake unsteadiness[17]. The wake rake was removed while the "Hump" model was tested.

2.3 NACA 0015 Airfoils

Two variants of a 254 mm chord NACA 0015 airfoil were tested. In the first configuration (Fig. 1), the airfoil was equipped with an excitation slot located on the upper surface at 10% chord, suitable for the control of separation near the leading edge. In the second configuration (Fig. 2), the airfoil was equipped with a 30% chord trailing-edge flap deflected by 20 deg with an excitation slot located at the flap shoulder (70% chord). In the latter case, the flow separates at the flap shoulder over a wide range of α and R_c's. Both slots were about 0.2% chord wide (0.50 and 0.44 mm for the forward and rear slots, respectively), and allowed a downstream introduction of excitation (inclined 30 deg to the surface). Each slot was connected to an internal cavity, into which pressure fluctuations were introduced. When using the aft slot and cavity, the leading-edge cavity was filled with acoustic absorbing foam to eliminate cavity resonance and the sides of the cavity were sealed to eliminate the possibility of mass transfer.

2.4 The "Hump" Model

The "Hump" model, with c=200 mm, simulates the upper surface of a 20% thick variation on the Glauert Glas II airfoil[18]. A moderate favourable pressure gradient up to 55% of the chord is followed by a severe adverse pressure gradient, imposed by the highly convex surface at x/c~0.6, that relaxes towards the trailing edge (see Fig. 3a). The model was mounted on the tunnel sidewall, where the upstream boundary layer was known to be turbulent. It has some common features with a backwards-facing step with the exception that the flow on this model can be fully re-attached with effective control. Without control, the flow separates at the highly convex region of the model (x/c=0.65, Fig. 3a) and a large turbulent separation bubble is formed. Periodic excitation is applied from the slot located at x/c=0.64 or at x/c=0.59 to gradually eliminate the separation bubble. The slots were about 0.25% chord wide (0.50 mm ±20%), and allowed a shallow angle downstream introduction of momentum (the slots are inclined 30° to the surface, see Fig. 3a). The "Hump" model design also enabled testing at a mild sweep angle. A photograph of the 3D configuration (Λ=30 deg) is shown in Fig. 3b. The dashed lines mark the location of the reference LE and TE. End plates isolated the boundary layers on the floor and ceiling of the wind tunnel thereby preventing distortion of the spanwise flow uniformity over the model. Ten dynamic pressure transducers were installed under the model surface, and were connected to the surface by orifices, 0.254 mm in diameter[19]. One dynamic pressure transducer was installed inside the model cavity to monitor the cavity pressure oscillations and provide an estimate of the slot exit velocities by correlating the pressure oscillations measured in the cryogenic experiments to those measured during bench-top slot calibration tests[5, 14].

2.5 Oscillatory Blowing System

The oscillatory blowing system is capable of introducing a wide range of steady and periodic momentum combinations from the cavity inside the models through the slots to the external flow. More details can be found in Refs. 5 and 14.

2.6 Bench-top Experiments

The velocity fluctuations exiting the slots of the models were measured outside the tunnel using a hot-wire mounted on a three-dimensional traverse system. The Nitrogen supplied to the oscillatory blowing valve during the wind tunnel test was replaced by compressed air. Scaling arguments[5], led to the development of correlations that were used to estimate $\langle c_\mu \rangle$ at the cryogenic pressurized conditions.

2.7 Experimental Uncertainty

The experimental uncertainty in the determination of C_p' amplitude was estimated to be ±15%. The estimation of the $\langle c_\mu \rangle$ was within ±25% of the quoted values. The steady c_μ's are within ±5% of the cited values or 0.01% absolute value (the bigger of the two). Additional uncertainty information can be found in Refs 5 and 14.

3. Discussion

3.1 Overview

The experimental results that are discussed in the following sections are a compilation of data that were acquired during four wind tunnel entries, and were presented and discussed in several publications[5, 14, 17, 19, 20]. Data were acquired on two configurations of a NACA 0015 airfoil (Figs. 1 and 2) and on the "Hump" model (Figs. 3a and 3b) at high Reynolds numbers (2-40x10^6) and a wide range of Mach numbers (0.2 to 0.7). Mild sweep angle, boundary layer thickness and excitation slot location were also considered. The discussion is arranged such that the parameter space is explored rather than a comprehensive description of a certain test. For a more comprehensive description of the experiments and the results, the reader is referred to the original papers.

3.2 The Effects of Reynolds Number and Excitation Frequency

Active separation control was applied successfully, for the first time, at Reynolds numbers corresponding to a jetliner at take-off conditions. Oscillatory flow excitation proved to be an effective and efficient tool for the control of boundary-layer separation over a wide range of chord Reynolds numbers, ranging from a micro-aerial-vehicle to a commercial jetliners at take-off[5, 6]. It was demonstrated, in accordance with low Reynolds number experiments (Fig. 4), that incompressible $C_{l,\max}$ can be increased by 15%, post-stall lift can be increased by as much as 50% and post stall drag can be reduced by more than 50% (Fig. 5) using low momentum oscillatory excitation applied close to the leading edge. The wake of the controlled airfoil is steadier than that of the baseline wake. Flap effectiveness can be increased when control is applied at the flap shoulder (Fig. 6). More importantly, when dimensionless frequency and amplitude parameters were maintained, the results are independent of the Reynolds number (Fig. 6).

The effective excitation frequencies were such that $0.5 < F^+ < 1.5$ regardless of the Reynolds number. This Strouhal number (F^+) is based on the length of the baseline-separated region. The same frequency scaling is applicable to turbulent separation bubbles. This was demonstrated using the "Hump" model, which simulates the upper surface of a modified Glaurt-Goldschmied airfoil (Fig. 3 here, Ref. 14 and References therein).

The baseline flow on the "Hump" model is fully turbulent, to eliminate the possibility of anomalies in the data trends resulting from laminar-turbulent transition. The Reynolds number has a very weak effect on the model pressure distributions and spectra, regardless of the Mach number or the sweep angle[14, 20]. The spanwise uniformity of the wall pressures, at 2D flow conditions, was found to be very good and improved as the separation was controlled. Without control, the flow separates at the highly convex area and a large turbulent separation bubble is formed (Fig. 7a). Control (steady or periodic) was applied upstream of separation (the slot location is shown by the dashed vertical line on Figs. 7), to gradually eliminate the separation bubble. The thickness of the upstream boundary layer was monitored and controlled. A reduction of 35-40% in the momentum thickness of the upstream boundary layer had a negligible effect on the mean and fluctuating wall pressures and had only a weak effect on the pressure spectra. It is speculated that flow separation on the "Hump" model (Fig. 3a) is caused mainly by the highly convex curvature and severe slope rather than by an adverse pressure gradient or viscous effects.

The baseline reattachment point on the "Hump" model was found to be about one separation height downstream of the peak in the wall pressure fluctuations (Fig. 7a). The level of this peak increased as reattachment moved forward due to control, regardless of the control method. Active control using periodic excitation is comparable to steady suction and significantly more effective than steady blowing (Fig. 8), when the integral parameters are considered.

Periodic excitation is capable of reattaching the flow in the mean sense, but is not capable of reproducing the same pressure jump across a slot as strong suction does (compare controlled data of Figs. 7a and 9a with that of Fig. 10). This is presumably since the periodic excitation relies on enhanced mixing that is by nature a convective phenomena rather than a local one that is generated by the severe suction. Steady suction or blowing with a momentum coefficient of 2-4% is required to fully reattach the flow to the model surface and recover the potential pressure distribution (Fig. 10).

It was found that the superposition of weak steady suction on the oscillatory excitation enhances the efficacy of the excitation for separation control (Fig. 9a). This occurs because the receptivity of the separated shear layer to the fundamental excitation frequency was enhanced (Fig. 9b). The superposition of steady blowing proved to be as detrimental on the "Hump" model as it was on the "Generic Flap" (Fig. 9b and also in Ref. 2), while it proved beneficial where separation occurred far downstream of the excitation slot on a mildly curved surface (Ref. 5).

Controlled 2D data shows that the separated shear layer over the "Hump" model is most receptive to F^+ in the range 1.5 to 2 and it amplifies these F^+'s (Fig. 7a). Once reattachment is initiated, the amplitude of the controlled perturbations decay as the structures are convected in the streamwise direction (Fig. 7b). The separated shear-layer is significantly more receptive to F^+=1 than to F^+=0.5 (Figs 11 a and b). Non-linear wave resonance between F^+=0.5 and F^+=1 plays an important role in the reattachment process (Figs. 11). Downstream of reattachment the low F^+'s decay, with the decay rate of higher harmonics being slower than those of the fundamental excitation frequency. It was demonstrated that the increased efficacy of low F^+, high $<c_\mu>$, excitation is through the generation of higher harmonics and non-linear interaction among the several excited waves (Fig. 11) with F^+ in the range 1.5 to 2 playing an important role.

The effect of weak steady suction, without periodic excitation, is to promote the generation and amplification of a wide frequency band of unsteady waves that evolve in a similar manner to the evolution of coherent excitation at F^+=1.6 (Fig. 12a and b). A comparison of the effects of the two modes of excitation shows again that the most unstable frequency bands for separation control on the "Hump" model are F^+~1.5 and also F^+~5.

3.3 The Effects of Compressibility

The significant increase in lift and lift to drag ratio, obtainable at incompressible speeds due to the application of periodic excitation upstream of the boundary layer separation location (as shown in Fig. 5, for example), should not be expected at compressible speeds. The global effect of the method is to accelerate the upstream flow (as seen in Fig. 13), compared to the baseline, due to the delay of boundary layer separation. At compressible speeds, this could lead to a stronger shock wave that in turn could cause a more severe separation that is less responsive to control. This process might saturate the effectiveness of the excitation at compressible speeds. In transonic flow, the method could be used to alleviate buffet, delay the occurrence of drag divergence and control local separations rather than generate higher lift.

Periodic excitation proved to be very effective when it was introduced only slightly upstream of the shock-wave (Fig. 14), increasing the lift-to-drag ratio, reducing the drag and causing a steadier wake (Fig. 15). Very low levels of phase-locked wake pressure fluctuations, at the excitation frequency, were measured in the controlled wake. A strong sensitivity of C_l, C_d and wake unsteadiness (W.U.) on $<c_\mu>$ was identified (Fig. 15). When excitation was introduced well upstream of the shock wave, it had a detrimental effect on lift, drag and wake steadiness. This is due to the creation of a localised disturbance at the excitation slot. This effect is not present at low Mach numbers. There, the introduction of wall-tangential excitation, far upstream of the boundary layer separation, resulted in a *smaller performance increment* (when compared to excitation that was introduced immediately upstream of the separation location), but did not result in absolute *performance degradation*.

Compressibility tends to elongate the baseline separation bubble (Figs. 16 and 17a), on the "Hump" model, due to reduced mixing above the separated shear-layer. Active control using periodic excitation is comparable to steady suction and significantly more effective than steady blowing, also at compressible speeds, as long as the modification of the integral parameters is considered (Fig. 18a and b). The capability of periodic excitation to shorten the separation bubble is reduced at compressible speeds, using similar non-dimensional frequencies and excitation levels (Figs. 16 and 17b). The separated, compressible shear-layer is not as receptive to the controlled excitation as its low Mach number counterpart (see C_p' in Fig. 17b). F^+ as low as 0.3 were found to be effective, but the efficiency increased with F^+ (up to 0.7 tested at M=0.65 on the "Hump" model).

3.4 The Effects of Mild Sweep

The effects of mild sweep were studied on the "Hump" model (Fig. 3b). It was found that the separation location is not sensitive to the sweep angle (Fig. 19a). The swept flow did not differ considerably from "infinitely" swept flow conditions. Steady as well as periodic control improved the spanwise uniformity at the lee side of the model[20].

The level of the wall pressure fluctuations in the 3D separated flow is significantly higher than in its 2D counterpart (Fig. 19a). This is a manifestation of the additional 3D streamwise vorticity that can roll-up to generate discrete unsteady streamwise vortices superposed on the spanwise vortices. Regardless of the mechanism, the result is a shortening of the 3D separated flow region (Fig. 19a).

The 3D attached boundary layer flow develops in a direction perpendicular to the leading edge and scales, as expected, with $1/\cos^2\Lambda$, where Λ is the sweep angle (Fig. 19b), while the separated shear-layer develops along the free stream direction and scales with $x' = x/\cos\Lambda$, x being the direction perpendicular to the LE (Fig. 19b).

It was demonstrated that the form drag and the excitation momentum (C_μ) agree with the conventional swept flow scaling ($1/\cos^2\Lambda$), when the flow is mostly attached (Figs. 20 and 21), using moderate to high C_μ levels.

The swept flow separation is more receptive to F^+=1 excitation than its 2D counterpart, and also reduces the random pressure fluctuations more effectively. Large $<c_\mu>$ excitation generates stronger coherent wave motion at higher F^+, and controls the random motion in the boundary layer more effectively. Conventional swept wing scaling works well also for the phase locked pressure wave features (Ref. 19, Fig. 16).

3.5 The Effects of the Excitation Slot Location

Based on numerous experiments, it could safely be stated that whenever controlled excitation was applied close enough to, but upstream of, the separation location, it proved beneficial, regardless of the Reynolds number, the Mach number the sweep angle or the surface curvature.

It was found that the presence of an excitation slot (width 0.25%c) does not affect the flow on the "Hump" model at low Mach numbers. The effectiveness of the excitation slot located just upstream of separation is significantly higher than the slot located 0.05c upstream of it, at low Mach numbers (Fig. 22). The data presented in Fig. 22, also shows that the different excitation slot locations do not alter the baseline flow conditions. The x/c=0.64 slot (dashed line) is more effective because the magnitude of the excitation at x/c=0.67 is larger for the excitation that was introduced from the x/c=0.64 slot. This indicates that the excitation is not amplified in the attached region of the boundary layer, regardless of the sweep angle.

At compressible speeds, the presence of an excitation slot located *upstream* of the shock wave alters the baseline pressure distributions (Fig. 23a and b). However, the effectiveness of the x/c=0.59 slot, when it is located under the shock wave, is greater than the effect of a slot located just downstream of the shock (x/c=0.64). The shock wave location and the separation line are usually very close. This eliminates the possibility of introducing the excitation downstream of the shock and still upstream of separation.

4. Recommendations

4.1 Applications

The result of introducing controlled excitation into a separating flow over an airfoil is not only to increase the lift and reduce the drag but also to reduce flow unsteadiness on the body and in its wake. The useful angle of attack range of an existing configuration can be extended this way.

Unsteady separation control could be used to simplify, reduce the weight, maintenance and cost of high-lift systems[21]. This aspect of the research is currently conducted in a low Re number wind tunnel*. Although the majority of the experiments conducted to date focused on airfoils, the same approach could be used to delay flow separation and overcome steeper adverse pressure gradients in diffusers, inlets, jet nozzles, aft fuselages and rotorcraft applications. Jet AFC is currently conducted both at LaRC and at TAU. AFC could increase the efficiency of conventional control surfaces, decrease their size, allow quicker handling of gusty conditions, and backup or even replace conventional control strategies. It is proposed to demonstrate this benefit in the RevCon program[22] on an unmanned advanced technology demonstrator vehicle.

4.2 Code Validation

The experimental database[14, 19, 20] presents an appropriate validation case for numerical simulation of unsteady flow control at high Reynolds numbers. The following reasons make this database useful:

1. The upstream boundary layer as well as the downstream flow conditions are not affected by the control that is applied to the model.
2. The incoming boundary layer is fully turbulent. Its parameters were measured and controlled.
3. The tunnel wall pressures were measured in order to assist in determining the wall interference.
4. The spanwise uniformity was monitored by off-centerline pressures.
5. Proper characterization of the periodic excitation is a precondition to performing a reproducible active flow control experiment. The slot u' was measured, using a comprehensive bench-top calibration test. The <cμ> at cryogenic conditions was linked to the bench-top calibration using theoretical considerations[5].
6. As a results of the actuation system design, the u' calibration of the "Hump" model is universal, i.e. independent of the excitation frequency.

4.3 Closed-loop Control aspects

Separation control using periodic excitation generates a mild and proportional response to changes in <cμ>, in the steady-state sense (Figs. 5, 8, 15, 18, 21). This makes the method suitable for closed-loop control applications.

Sensing methodology such as measuring the mean dP/dx, using only two pressure taps, proved to be a possible closed-loop approach[23] in 2D flows. Local skin friction measurements should be tested in combination with measurement of unsteady pressure gradient.

However, the transient time scales[24-26] of the flow response to generic control inputs proved to be somewhat slow and the behaviour somewhat resembled an under damped 2nd order system. A closed loop control method should attempt to shorten and smooth these transients.

4.4 Further Research and Development

The relationship between laminar-turbulent transition and separation control is a complicated open issue, especially at sub-critical (in the linear sense) Reynolds numbers. In most experiments conducted to date we attempted to bypass the problem by tripping the boundary layer prior to separation in order to eliminate transition from contaminating the Reynolds number trends and changing the baseline mixing-rates abruptly. At Low Re numbers, transition and separation are interconnected and could not be studied independently. While intellectual and scientific reasoning call for unbiased comparison between the effects of passive tripping and active BLC, practical considerations call for active separation control of the laminar boundary layer without pre-transitioning the boundary layer. This would significantly complicate the optimization of the active

* on-going research, Seifert, Jenkins and Pack, NASA LaRC.

separation control procedure, but would hopefully result in a more efficient system.

Multiple slot, multiple frequency actuation should be studied in combination and separately in order to find innovative approaches to overcome the lack of sufficient control authority, especially at high speeds. Proper use of the non-linear response of the separated shear-layer to high amplitude excitation should enable the optimization of available actuator output to generate the maximum response of the boundary layer. Improving the receptivity of the separated shear layer to the excitation input, as was done by the superposition of weak suction (Figs. 9a and b and in Ref. 14), is one possible approach.

The design, fabrication and proper characterization of efficient actuators, that have sufficient control authority, are still a major challenge and are a precondition to performing flight experiments. Most cavity-installed actuators perform very well around 1KHz, while the most efficient excitation frequencies for large size controlled surfaces (order of 1 m) at low speed (say 70 m/s) call for an order of magnitude lower frequency. In that respect we should investigate amplitude modulation of high frequency excitation and compare its effect directly to low frequency excitation.

Advanced closed loop control methodologies, preferably using 3D real-time wall shear-stress sensors and or unsteady wall pressure gradient, surface or cavity installed actuators and modern control strategy should be developed. The answer to the question: "What do we control and how?", depends on the purpose of the control effort.

Design tools should hopefully assist and direct the research and development; not only as a post-production tool of experimental data. There are several numerical procedures (such as LES, DES, time accurate RANS) and a clear validation and performance optimization are yet to be performed.

Comprehensive experiments that combine hot wires for slot calibration, actuators' real-time monitoring, space parameters monitoring, unsteady pressures, PIV and 3D skin friction measurements to provide real-time data for open- and closed-loop control should be performed.

Two major open subjects for further research are the effects of curvature on AFC and understanding and utilization of 3D excitation modes.

5. Summary

Active separation control, using oscillatory flow excitation, was tested and proved successful in delaying boundary layer separation and reattaching separated flows at chord Reynolds numbers of order 10^7. The method proved beneficial also at compressible speeds, as long as the excitation was introduced slightly upstream of the shock-wave foot. Separated flows on mild swept configurations are also very receptive to the control input, but more complex to analyze. Additional modes of unsteady perturbations await analysis and utilization. Steady momentum transfer, alone or superposed on the periodic excitation, was also tested and its efficacy was assessed. Periodic excitation proved to be at least comparable to steady BLC control, over the entire parameter space, and could be combined with weak steady suction to enhance its effectiveness. Somewhat surprisingly, steady blowing became more effective than steady suction at compressible speeds.

It is recommended to focus near term research on the following tasks:

1. Development and validation of numerical design tools,
2. Development of efficient and robust actuators, especially for high speed applications,
3. Development of closed-loop control methodologies, integrated with sensors, actuators and control circuitry, and
4. Conduct fundamental, comprehensive, coordinated, analytical, numerical and experimental investigations in order to deepen our understanding of this exciting area of research.

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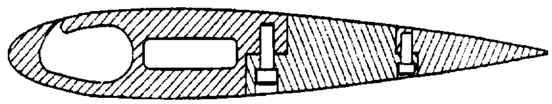


Fig. 1 NACA 0015 airfoil with an excitation slot at X/c=10%.

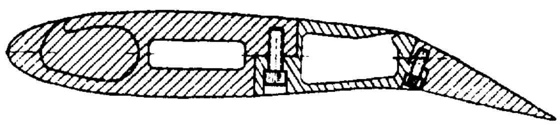


Fig. 2 NACA 0015 airfoil with a 25% trailing edge flap deflected 20 deg and a blowing slot at X/c=75%.

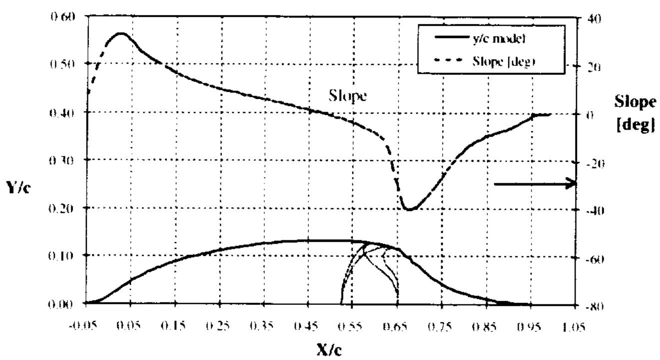


Fig. 3a The "Hump" model with its slope and excitation slots at X/c=59 and 64%.

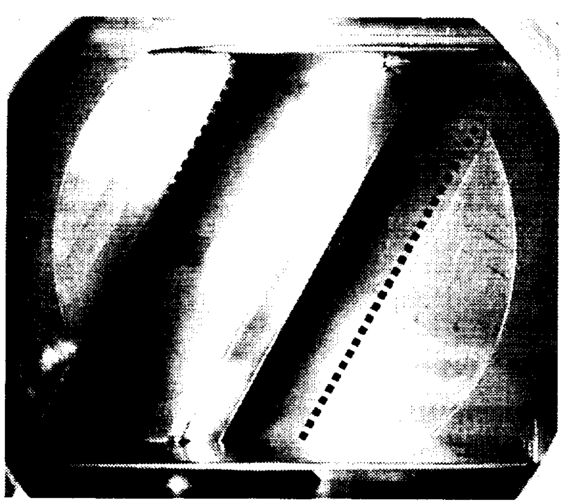


Fig. 3b A photograph of the swept "Hump" model with an excitation slot at X/c=0.64, as installed in the 0.3m TCT. Flow is from left to right. The white dotted line marks the reference leading edge and the black dotted line marks the reference trailing edge.

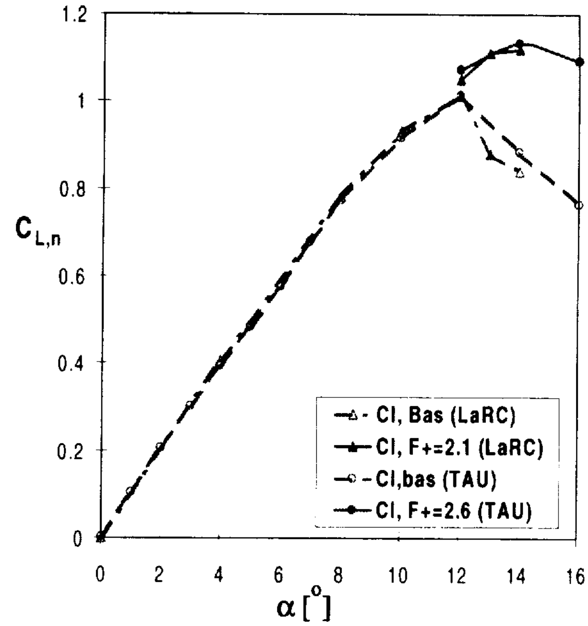


Fig. 4 Baseline and controlled lift of NACA 0015 airfoils Measured at R_c=0.9x10^6 (TAU) and R_c=37.6x10^6. Cμ~(0.15;0.04)%.
Note that all data are normalized by $Cl,_{max}$ of baselines.

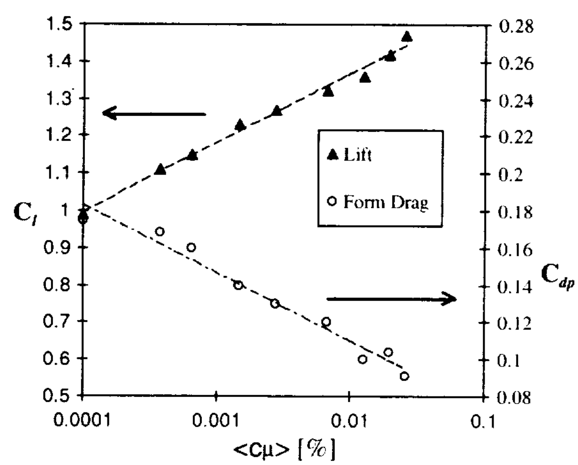


Fig. 5 The response of the straight NACA 0015 airfoil lift and Form-drag to gradual change in the magnitude of the LE excitation.R_c=12.7x10^6, M=0.28, α=14 deg, F$^+$=2.1.

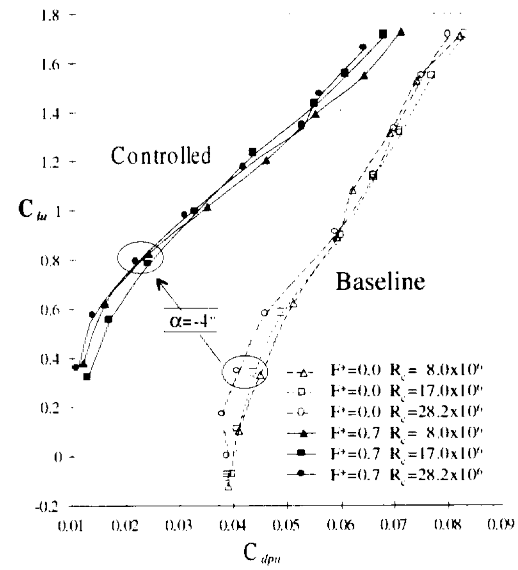


Fig. 6 Baseline and controlled lift-form drag polar of the flapped NACA 0015. M=0.2, δ_f=20 deg, Cμ~(0.00;0.05)%.

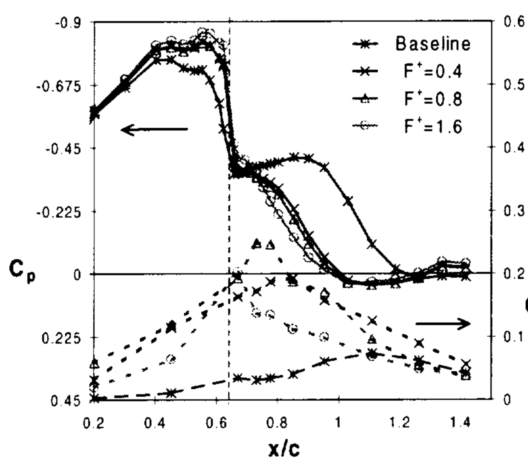


Fig. 7 Baseline and controlled mean and fluctuating "Hump" wall pressures. $R_c=16\times10^6$, M=0.25, <cμ>=0.13%.

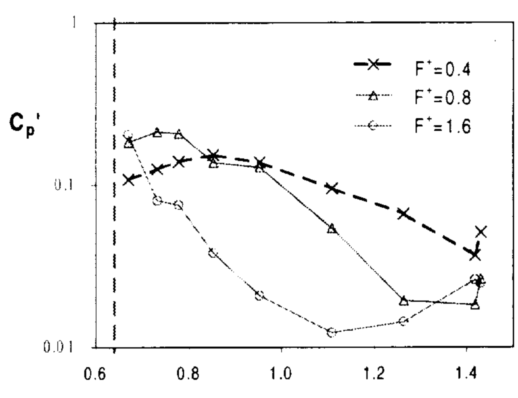


Fig. 7 Phase-locked pressure fluctuations corresponding to the controlled data of Fig. 11a.

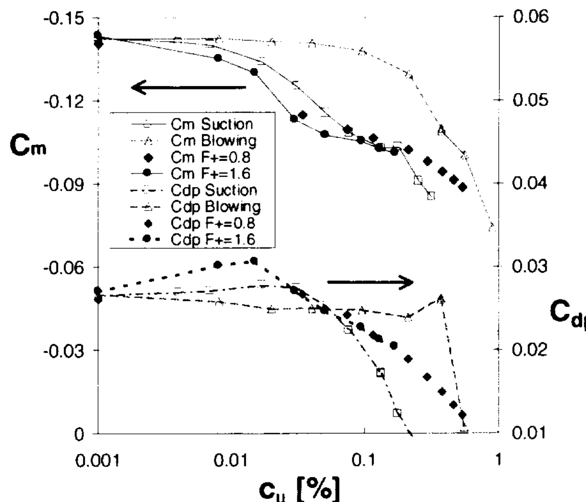


Fig. 8 The effectiveness of steady and oscillating momentum in modifying the "Hump" model integral parameters. $R_c=16\times10^6$, M=0.25.

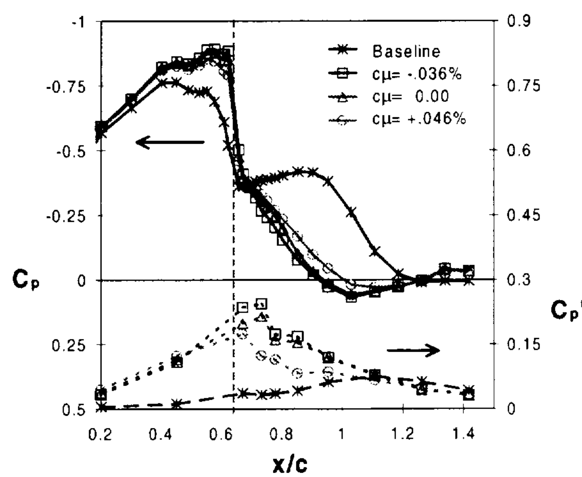


Fig. 9a The effect of the mean momentum transfer on the efficiency of periodic excitation over the "Hump" model. $R_c=16\times10^6$, M=0.25, F+=1.15, <c_μ>=0.23%. Dashed line indicates excitation slot.

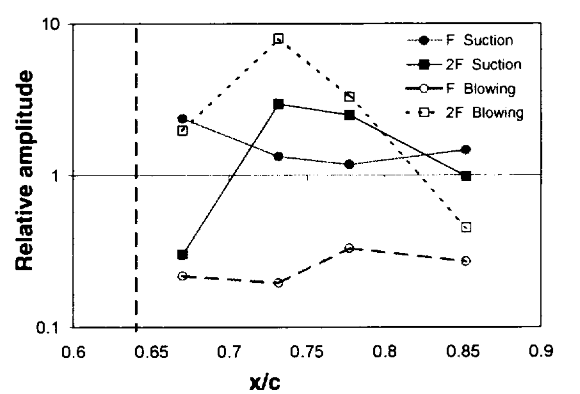


Fig. 9b The effect of the mean momentum transfer on the phase locked C_p' at the fundamental (F) and its 2nd harmonic (2F). Relative power of 1 is the cμ=0 case. Conditions as in Fig. 12a .

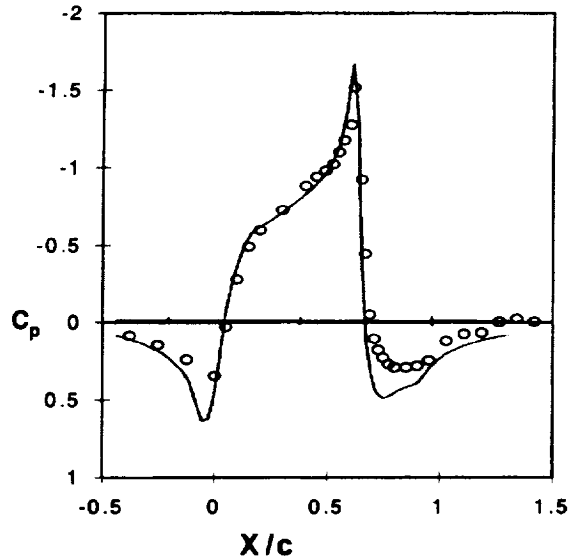


Fig. 10 Potential pressure distribution (line) and measured C_p of the "Hump" model using suction with cμ≈4%.

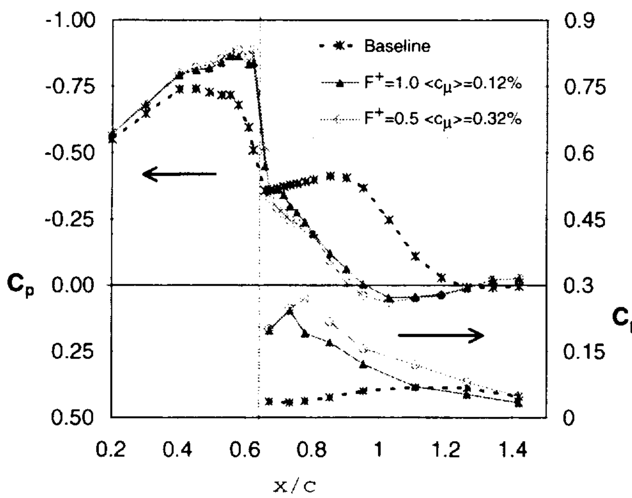
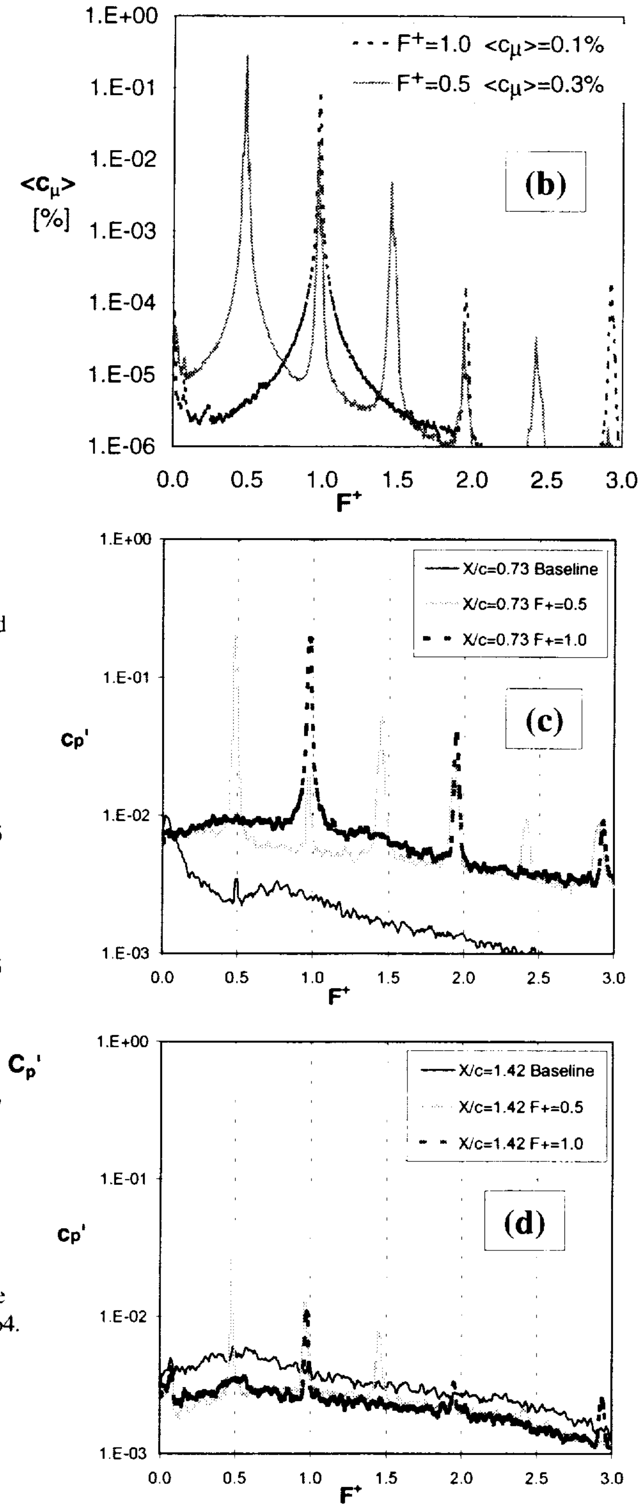


Fig 11a Mean and fluctuating wall pressures of the baseline and controlled 2D flow. $R_c = 4.2x10^6$, M=0.25, slot x/c=0.64.



Figs 11b-d Spectra of input (b), and wall pressure fluctuation for 2D baseline and controlled flows measured at x/c=0.73 (c), x/c=1.42 (d). $R_c = 4.2x10^6$, M=0.25, slot x/c=0.64.

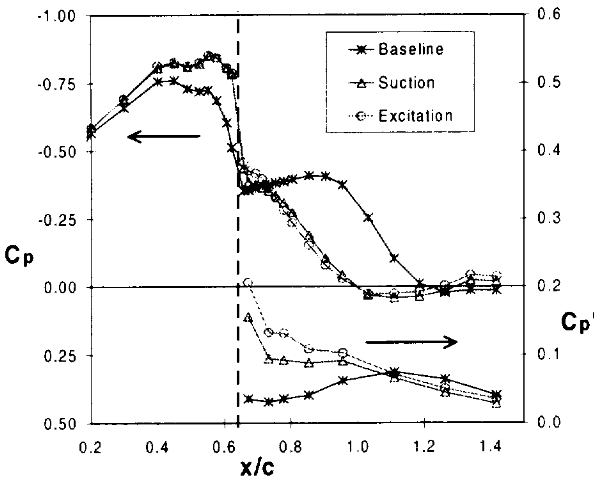


Fig 12a Mean and fluctuating wall pressures of the baseline and controlled 2D flow using suction (cμ=-0.08%) or periodic excitation (<cμ>=0.09%) , $R_c = 16\times10^6$, M=0.25, slot x/c=0.64.

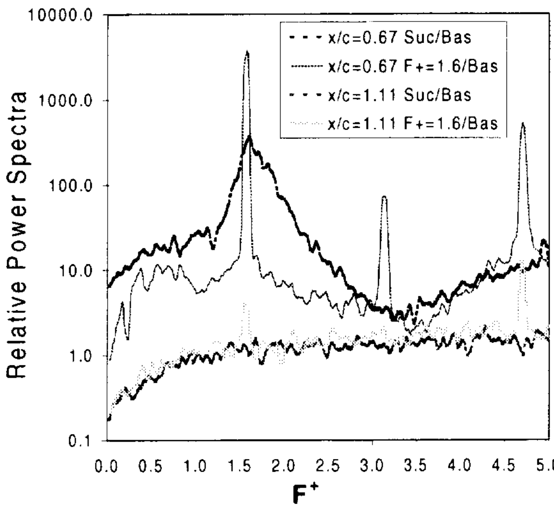


Fig 12b Wall pressures spectra of the controlled 2D flow normalized by the baseline spectra. Same conditions as the data of Fig. 24a.

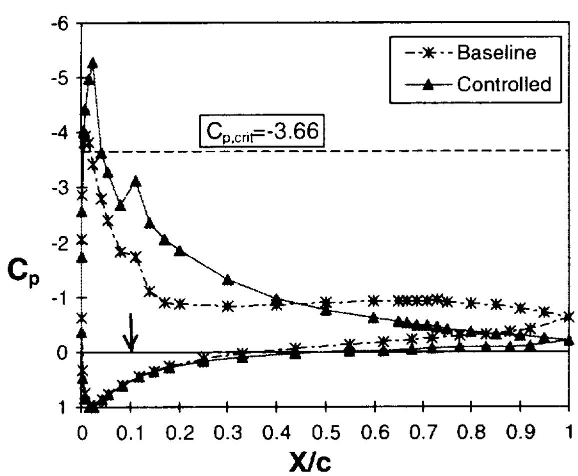


Fig. 13 NACA 0015 pressure distributions. M=0.4, $\alpha=11^0$, $R_c=12.7\times10^6$, $F^+=2.1$, $<c_\mu>=0.025\%$. Arrow indicates excitation slot.

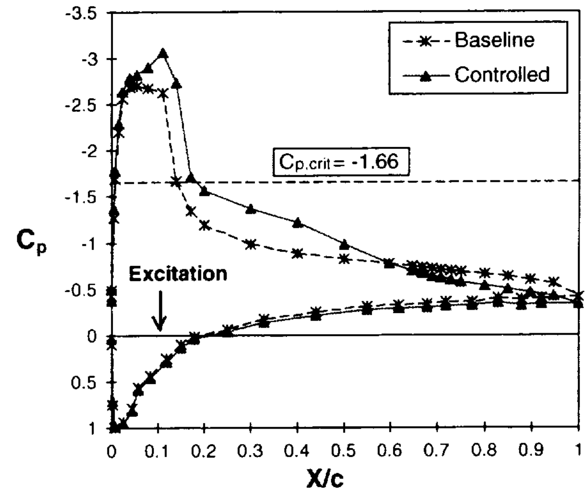


Fig. 14 Baseline and controlled airfoil pressures. $R_c=19\times10^6$, M=0.55, $F^+=1.65$, $<c_\mu>=0.015\%$, $\alpha=9^0$. Arrow indicates excitation slot.

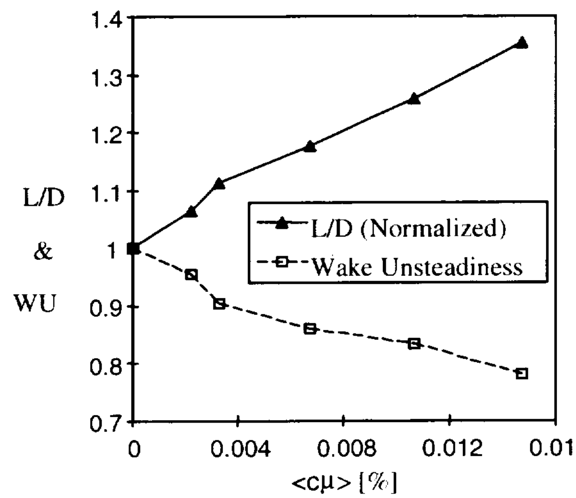


Fig. 15 Baseline and controlled NACA 0015 lift to drag ratio and integrated wake unsteadiness vs. excitation magnitude, both normalized by their baseline values. $R_c=19\times10^6$, M=0.55, $F^+=1.65$, $\alpha=9^0$.

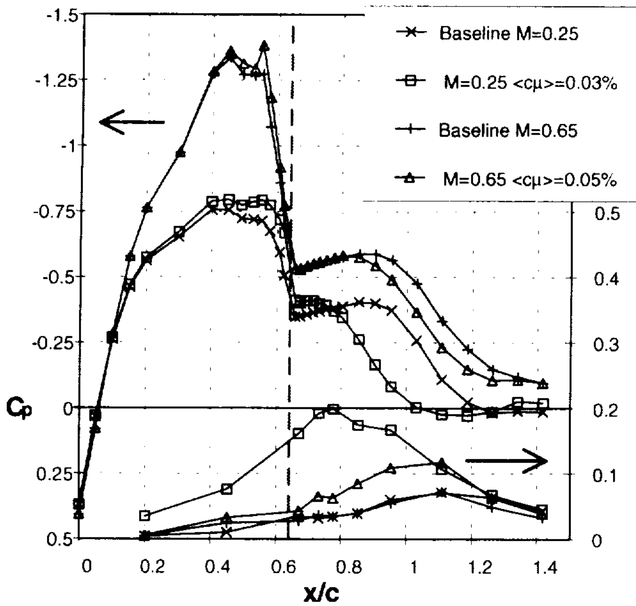


Fig. 16 A comparison of baseline and controlled 2D pressure distributions, M=0.65, R_c= 30x10^6, F$^+$=0.3 and M=0.25, R_c= 16x10^6, F$^+$=0.4.

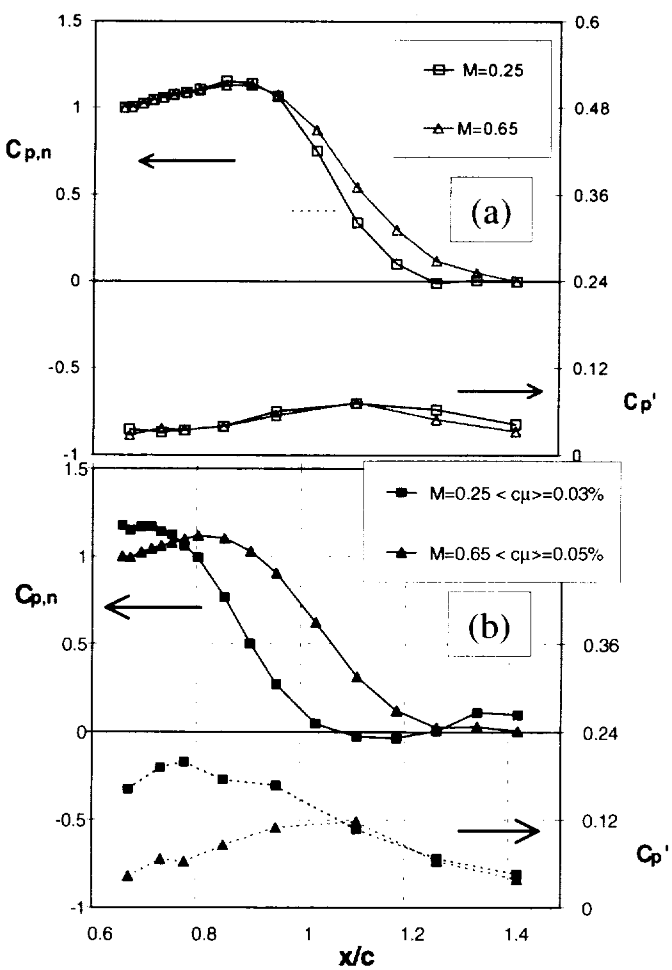


Fig. 17 A comparison of baseline, (a) and controlled, (b) 2D pressure distributions, M=0.65, R_c= 30x10^6, F$^+$=0.3 and M=0.25, R_c= 16x10^6, F$^+$=0.4.

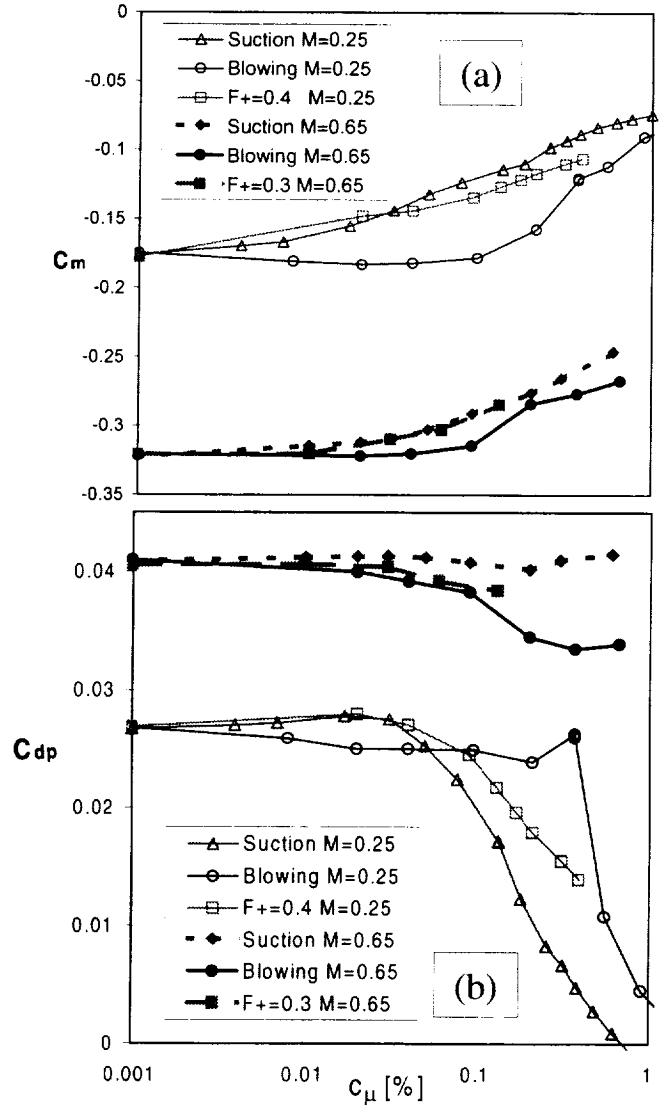


Fig. 18 The effect of steady and periodic momentum addition on the 2D integral parameters, M=0.65, R_c= 30x10^6, and M=0.25, R_c=16x10^6, x/c=0.64 slot: moment coefficient (a), form drag (b).

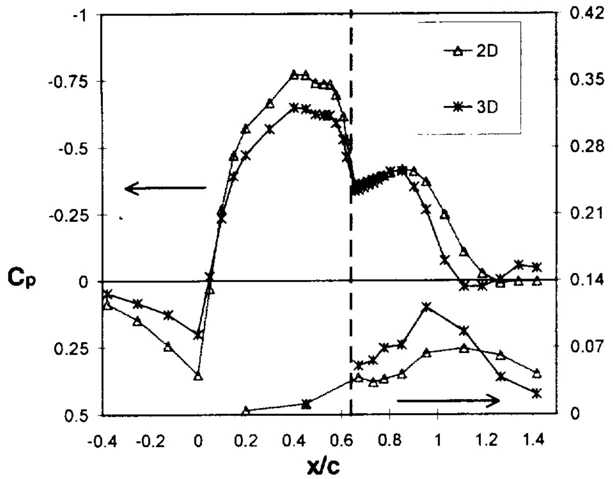


Fig. 19a A comparison of pressure distributions for zero and 30 deg sweep angles, M=0.25, R_c= 16x10[6]

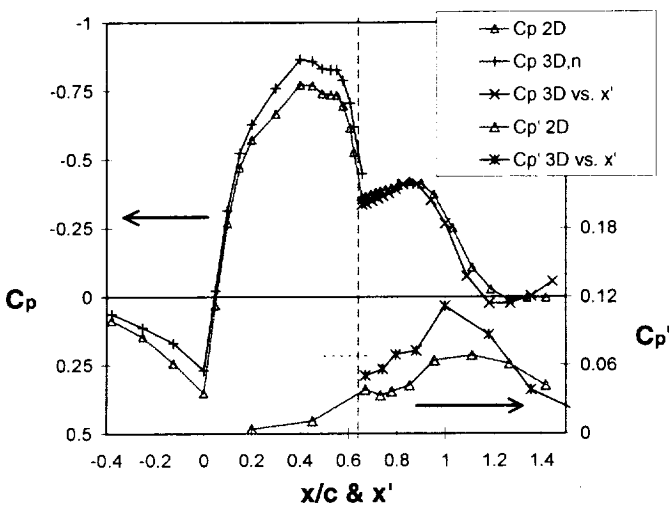


Fig. 19b Scaling of pressure distributions for zero and 30 deg sweep angles, M=0.25, R_c= 16x10[6].see text for notation.

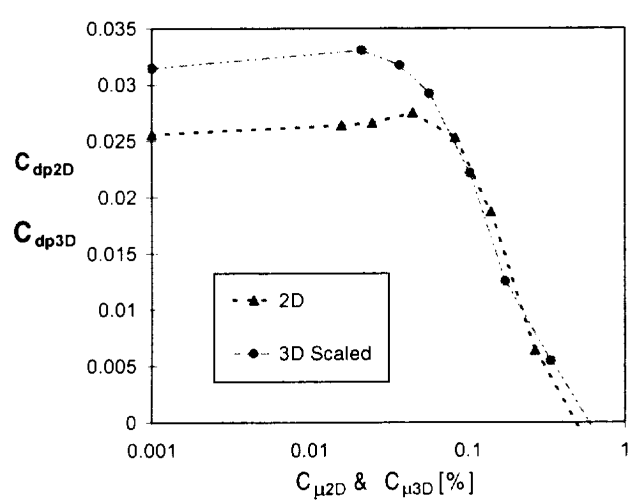


Fig. 20 The effect of sweep on the scaled form-drag using steady suction for control, M=0.25, R_c= 21x10[6], x/c=0.64 slot.

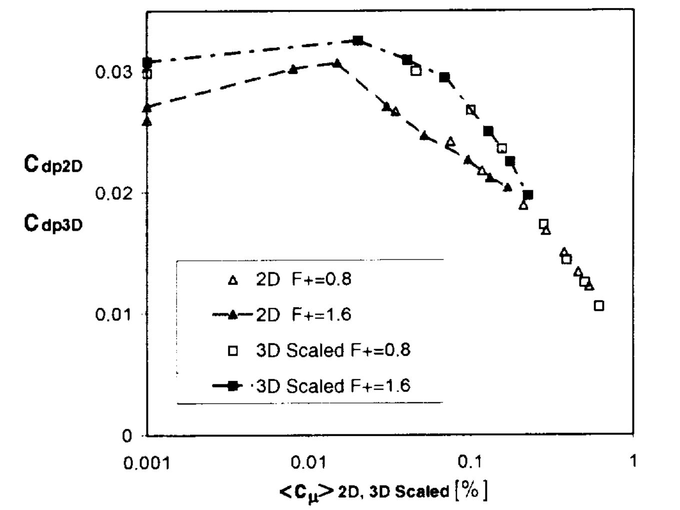


Fig. 21 The effect of sweep on the scaled form-drag using F^+=0.8 and 1.6 for control, M=0.25, R_c= 16x10[6], x/c=0.64 slot, cμ=0.

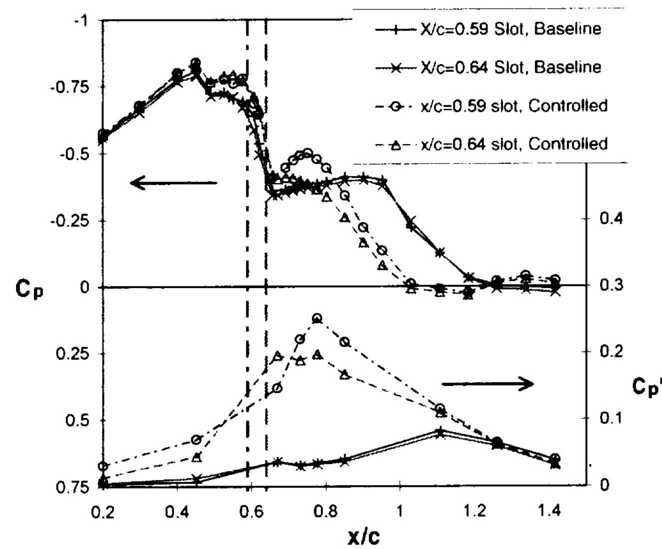


Fig. 22 The effect of the slot location on Cp and Cp' using F^+=0.8 for control, M=0.25, R_c= 21x10[6], <cμ>=0.06%.

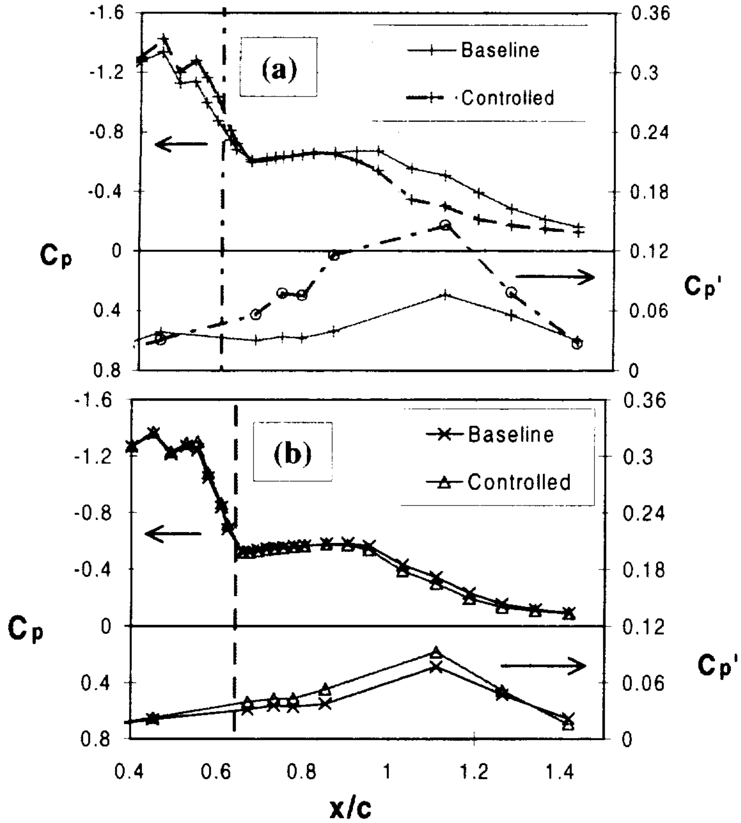


Fig. 23 The effect of $F^{+}=0.62$ and $\langle c\mu \rangle=0.03\%$ on Cp & Cp', M=0.65, $R_c= 29\times10^6$: (a) x/c=0.59 slot, (b) x/c=0.64 slot. Vertical broken lines indicate slot locations.