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ON THE INTERACTION BETWEEN STEADY AND OSCILLATORY ADDITION OF MOMENTUM IN THE CONTROL OF SEPARATION.

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ABSTRACT

The addition of weak, steady blowing to periodic perturbations of comparable momentum had detrimental effect on the control of separation over a deflected flap. The strength of the steady blowing had to surpass a certain threshold in order to overcome the damage. The purpose of this study was to investigate this effect and attempt to explain it. The experiments were carried out over a deflected, straight flap. Instantaneous pressure measurements were made over the entire surface while concomitantly two components of velocity were measured above it by using a particle image velocimeter (PIV).

INTRODUCTION

The effects of periodic perturbations on improving the performance of airfoils in general, and flapped airfoils in particular, is by now well established[1-3]. Various experiments confirmed these observations for Reynolds numbers ranging from 10^5 to 10^7, for a wide range of subsonic Mach numbers[4-5] and even for sweep-back[6]. A parametric study of the predominant variables affecting the flow over a deflected flap was carried out by Nishri and Wygnanski[7] where some observations describing the mechanisms of separation and reattachment were also made. These experiments were carried out on flaps of different length, using different means to perturb the turbulent boundary layer over the flap shoulder whose thickness was also artificially changed.

Initial observations suggested that steady blowing along the surface of a deflected flap, over which separation occurs may maintain the downward flow direction in the immediate vicinity of the surface but not above it. A region of reverse flow, bound by the jet below and the free-stream above, was observed in the midst of the thick decelerating boundary layer because the added jet momentum could only maintain the downstream direction of the flow near the surface. The flow in this region was highly agitated because the shear layers bounding it rolled up into vortices which were periodically swept downstream. Externally introduced oscillations at a knee of a flap created large eddies which spanned the recirculating zone and transported momentum from the free stream to the surface. The average velocity, in what used to be the recirculating zone, changed its direction due to the excitation and appeared as a thick, well-mixed boundary layer. The externally introduced periodic motion enhanced the generation of the large coherent structures, which enabled the flow to withstand more adverse pressure gradients.

It was generally observed that the dimensionless periodic momentum coefficient, $<c_\mu>$, required to prevent separation can be one to two orders of magnitude smaller than the corresponding steady C_μ required to achieve a comparable task. The comparison of this method of separation-control with steady blowing generated some peculiar results primarily when the injected momentum in both cases was small but of comparable magnitude. Therefore a study that endeavors to determine the significance of each parameter and some leading interactions among them was initiated over a straight flap. This is a generic configuration because there is no curvature involved, it is sensitive to small changes in pressure gradient, and has a well-defined location of separation. The experimental apparatus is described in detail in [7]. The pressure distribution over the entire flap could be almost instantaneously acquired (within 2ms) while a particle image velocimeter would interrogate the velocity field concomitantly. When the data from 500 picture-pairs acquired randomly was processed the results compared

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within 5% to the statistically processed hot-wire data in regions in which flow reversal did not occur. No such comparison could be made in the interior of a "bubble" because the conventional hot wire is not sensitive to changes in flow direction in a plane normal to the wire.

RESULTS AND DISCUSSION

At small flap deflections the pressure gradient is well predicted by ideal flow approximation. At larger deflection angles a bubble is formed and it grows rapidly with increasing deflection angle α, leading to a complete separation.

The pressure distribution shown in figure 1 started with the flow being separated at $Re=450*10^3$ and $(\alpha-\alpha_r)=1.5°$ where α_r denotes the flap deflection at which the flow reattaches naturally. By adding a steady blowing at $C_\mu=100*10^{-5}$ the flow did not reattach. It did so when $C_\mu=180*10^{-5}$ enclosing a large bubble that extended over most of the flap. The bubble was still present at $C_\mu = 400*10^{-5}$ (fig. 1) in the absence of oscillatory input. Reducing slowly the intensity of the blowing resulted in total separation when $C_\mu=180*10^{-5}$. Flow reattachment by oscillatory means required only $<c_\mu>=12*10^{-5}$ at a reduced frequency of $F^+=1.5$ while separation was prevented at $<c_\mu> < 2*10^{-5}$ and $F^+=3$. These were close to the optimal frequencies for the respective conditions and they are discussed in detail in reference [7].

A combination of steady and oscillatory blowing was not very effective in this case either, because the slot was located at the place where natural separation occurred and there was no need to advect the imposed oscillations further downstream. For example, oscillatory amplitude of $<c_\mu>= 20*10^{-5}$ generated a bubble that covered less than 40% of the flap chord (according to the criterion discussed in [7]), and had a minimum Cp= -0.8 (fig. 1). The steady C_μ of $400*10^{-5}$ did not do as well, as it contained a bubble whose length was 60% of the chord. A combination of steady and oscillatory blowing at a combined $c_\mu=[100;\ 20]*10^{-5}$ (i.e. at $C_\mu=100*10^{-5}$ & $<c_\mu>= 20*10^{-5}$) was inferior to purely oscillatory blowing at $<c_\mu>= 20*10^{-5}$. A combined $c_\mu=[180;20]*10^{-5}$ is required to achieve, in this case, the same results as the oscillatory blowing alone. Another measure reflecting the state of the flow is the displacement thickness δ^* that was thinner everywhere when $c_\mu=[0;\ 20]*10^{-5}$ than it was at $c_\mu=[100;\ 20]*10^{-5}$. Measuring δ^* for various intensities of combined c_μ reveals clearly the detrimental effect of steady blowing, provided $C_\mu < 180*10^{-5}$. Only above this threshold, an increase in C_μ results in reduction of δ^*.

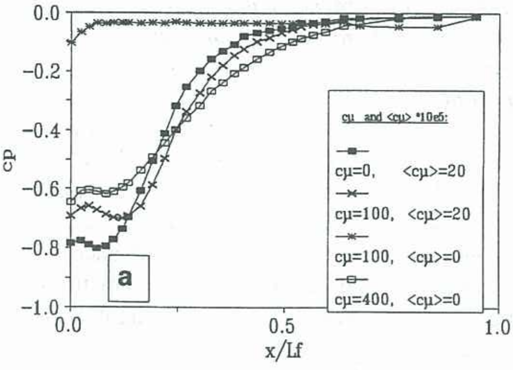

Figure 1 The effects of steady, oscillatory and combined blowing on the pressure and boundary layer thickness over a flap.

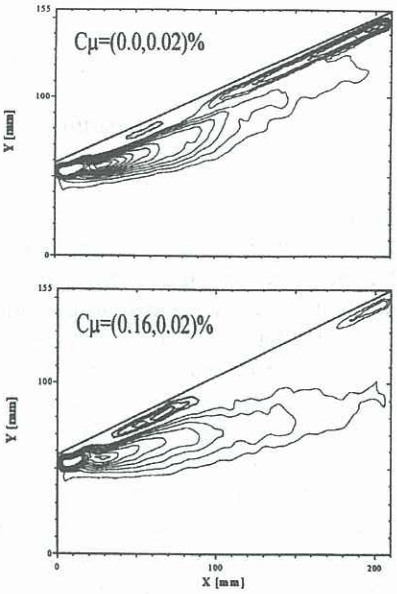

Figure 2 The effect of adding steady $C_\mu=0.08\%$ to a prescribed $<c_\mu> = 0.01\%$ on the mean vorticity distribution over the flap.

The particle image velocimeter (PIV) enabled us to assess the state of the entire flow over a short flap (of length 200mm) at any instant relative to the imposed oscillations introduced at its shoulder. When the PIV was triggered randomly and the data was ensemble-averaged over many events it yielded the mean flow parameters. The mean vorticity distribution over the flap in the absence of steady blowing is shown in figure 2a and in its presence in figure 2b. The closed contours near the surface represent negative vorticity indicating the presence of reversed flow, while the rest represent positive vorticity. In the absence of steady blowing the mean flow reattaches to the surface around 40% of the flap length as it was also deduced on the basis of the pressure distribution (fig. 1). The positive vorticity downstream of the mean reattachment position indicates a high level of skin friction, suggesting that separation is not imminent. The addition of steady blowing at a combined c_μ= $[160;20]*10^{-5}$ resulted in a longer and thicker bubble that extended over 80% of the flap and a weak positive vorticity region downstream of reattachment. Clearly, this is an undesirable effect.

The phase-locked vorticity contours reveal the presence of two temporary reversed flow regions (fig. 3) when $< c_\mu >$ =0.01%. The regions of negative vorticity extend at times to 70% of the flap length. Two, distinctly separate reversed flow regions coexist over the flap during 50% of the forcing cycle (fig. 3). Thus there are cells of forward flow, which are separated by regions of reverse flow near the surface. Each region of negative voricity is bound by the wall and by a region of positive vorticity. The region of negative vorticity is almost stationary during its initial

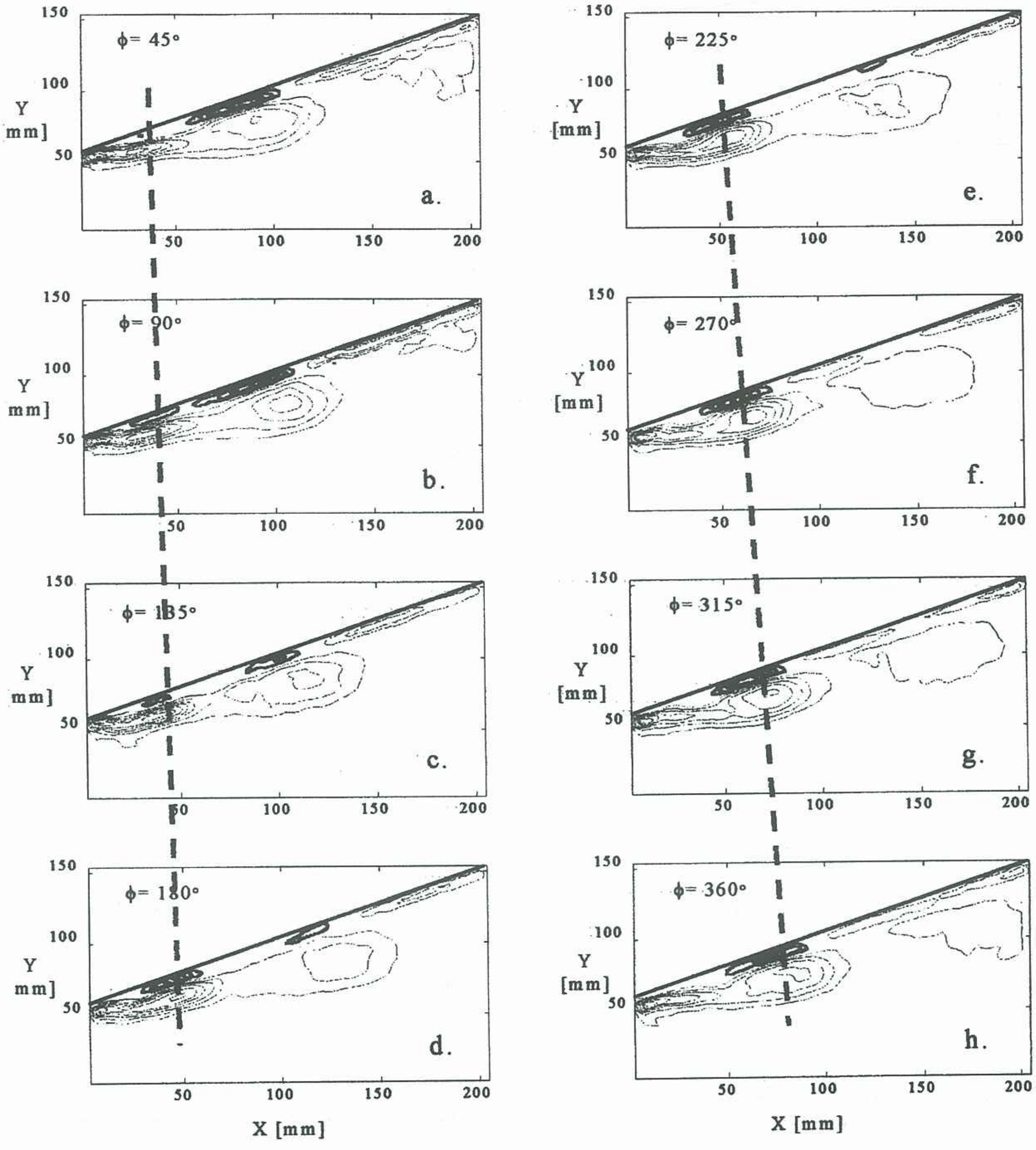

Figure 3 The changes occurring in the phase-locked vorticity distribution over the flap during one forcing cycle.

generation and intensification process (i.e. during its roll-up). The positive vortex sheet surrounding it is stretched in the process and its maximum intensity splits into two focal regions: one attached to the upstream boundary layer from which the vorticity is being shed and the second rolls up into a typical elliptical vortex form. The rolled up vortex is advected downstream at almost a constant velocity. The positive vorticity weakens after the separation of the vortex from the stationary vortex sheet (or mixing layer). The negative vorticity is initially enhanced by the roll-up process before decaying further downstream. It requires approximately 130 mm for negative vorticity to dissipate in this case. The attached vortex sheet (i.e. the shear layer) flaps like a flag due to the imposed oscillations and spawns a new region of negative vorticity. The imposed oscillations regulate the process allotting ½ of the forcing period to build up the vortex and the other ½ to separate it from the attached shear layer. When the separation is complete, the vortex travels downstream and decays. If the decay of the negative vortical region is not accomplished before the vortex reaches the trailing edge of the flap, the entire cycle is broken and the flow separates. By reducing the $< c_\mu >$ or by lowering F+, the roll-up and intensification process would be given the opportunity to create a sufficiently large vortex which will not decay while being advected to the trailing edge causing a complete detachment of the flow from the surface. This process will create what the rotorcraft community refers to as the "Dynamic Stall Vortex" even though the flap itself does not oscillate.

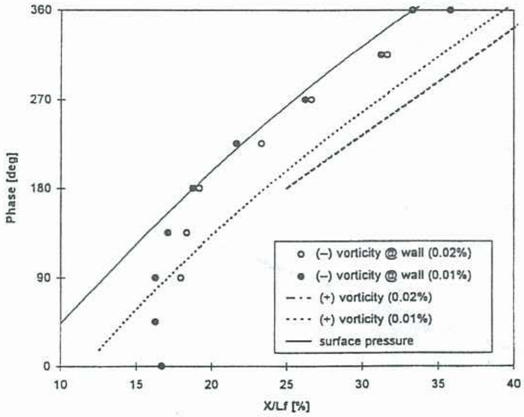

Figure 4 The location of the vortical cores over the flap during various phases of the forcing cycle, a comparison with the phase of the pressure signature.

The presence of the shear layer adjacent to the solid surface over which the flow is reversed may initiate the conditions for a temporary "vortex-capture"[8] during a portion of the forcing cycle. During this period the amplification of the coherent disturbance will reach a maximum while its phase velocity is insignificant. This seems to happen during the intensification cycle of the negative vorticity (fig. 4). The core of the positive lump of vorticity accelerates initially but thereafter it propagates with a constant speed over most of its journey over the flap. The addition of moderate steady blowing convects the eddy downstream during its amplification cycle and changes the stability characteristics of the entire shear layer, inhibiting the transfer of momentum across the flow near the leading edge of the flap where it is needed most. This may be the explanation for the detrimental effect of the steady blowing.

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