9th Osborne Reynolds Colloquium and Research Student Award
Department of Aeronautics - Imperial College London
16th June 2011

LAMINAR FLOW COMPRESSOR BLADES

Martin N. Goodhand
Whittle Laboratory
University of Cambridge
UK

Laminar boundary layers have lower skin friction than an equivalent turbulent layer. This property has long been exploited in the pursuit of low drag aerofoil sections for use on aircraft wings, but has not, until now, been used on the compressor aerofoils in jet engines. In this paper a method, developed in collaboration with Rolls Royce during my PhD, which can achieve this is described. By carefully controlling the aerofoil's leading edge geometry it was found that significant extents of laminar flow could be maintained over the aerofoil's suction surfaces. These new, laminar flow compressor blades have recently been used to reduce the fuel consumption of the *Airbus A330.* By upgrading all the leading edges in the *Trent 700 EP, Rolls Royce* demonstrated a reduction in fuel burn of 1.3% (Norris 2008).

These fuel burn reductions arise through two mechanisms. The first is a reduction in profile loss; the second is a reduction in loss generated close to the endwalls. This endwall loss, as it is known, is reduced by the suppression of a deleterious three-dimensional separation that exists between the blade's suction surface and the endwall; a schematic of the two cases is shown in Figure 1. The consequence on loss is also shown in Figure 1. Plotted are contours of stagnation pressure deficit taken downstream of a row of stators in a large-scale, low-speed compressor ($M{\sim}0.1$ $Re{\sim}3x10^5$). The right hand blade has fully turbulent boundary layers giving a thick deep wake at mid-span and a large loss core at both endwalls; the left hand blade has laminar flow over the early suction surface leading to a thinner, shallower wake and smaller loss cores. By using the laminar flow leading edge overall loss is reduced by 30%. The plots are shown adjacent for comparison, in the experiments the test blade was surrounded by the same geometry.

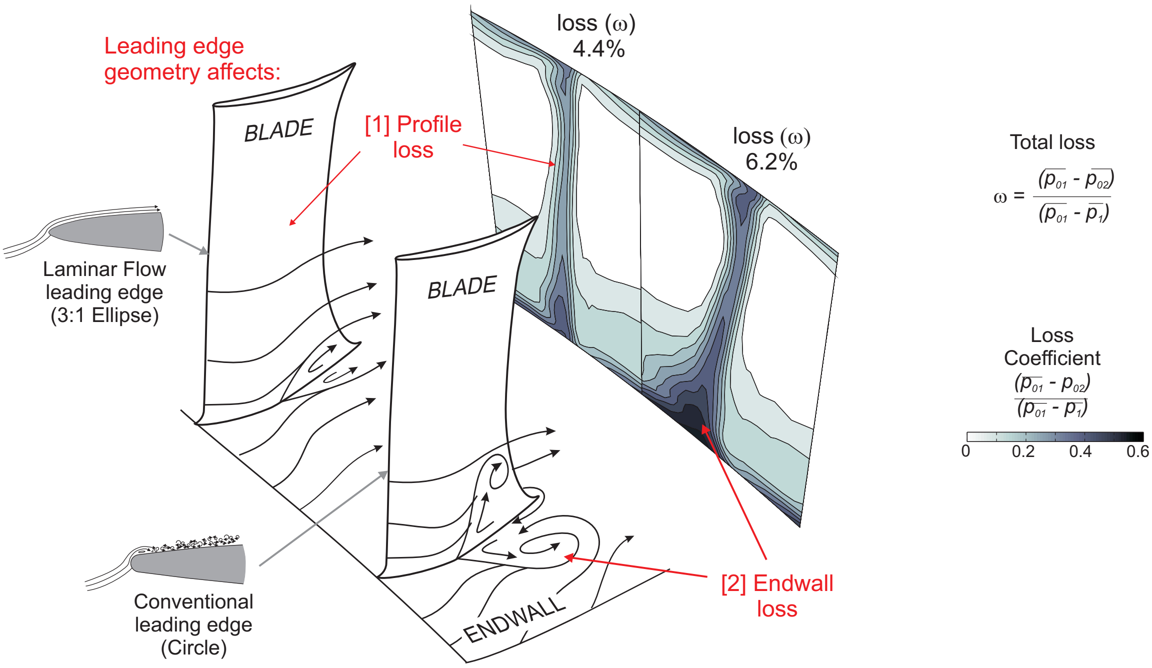

Figure 1 – The benefit of laminar flow leading edges: Schematic of surface limiting streamlines and plots of stagnation pressure deficit measured downstream.

The question therefore arises as to why engine companies had not discovered that the flow was so sensitive to leading edge geometry before. The first reason is that few believed that laminar flow was possible within the highly turbulent environment of a jet-engine compressor (*Tu* ~ 4%) and had thus dismissed it. The second reason is that with limited experimental capability they rely on computational models to predict component performance. In these Reynolds Averaged Navier-Stokes (*RANS*) models the flow is fully turbulent precluding the presence of laminar boundary layers; the leading edge geometry is therefore predicted to have little effect. The third reason is that leading edges are very small, typically 0.5mm in thickness; this makes them difficult to manufacture accurately and also requires designers to thicken up the leading edge in order to ensure that they have adequate strength.

The problem with making the leading edge thicker is that a "spike" appears in the surface pressure distribution close to the leading edge, as shown schematically in Figure 2. On conventional compressor blades, where a circular arc leading edge is used, the diffusion associated with this spike is enough to cause the boundary layer to briefly separate before reattaching turbulent. For laminar flow to be achieved the spike would therefore have to be small enough to prevent this separation. In order to practically design such a leading edge two constraints would have to be met. Firstly it would have to have adequate structural strength (thickness) and secondly it would have to operate efficiently over a wide incidence range; the latter being important for engine stability and performance away from the cruise condition. Conventional wisdom suggests that to reduce the spike, and thus cruise incidence loss, a sharp leading edge is best; however, it also suggests that a sharp leading edge will curtail the incidence range because the spike would grow rapidly with incidence; this implies a compromise.

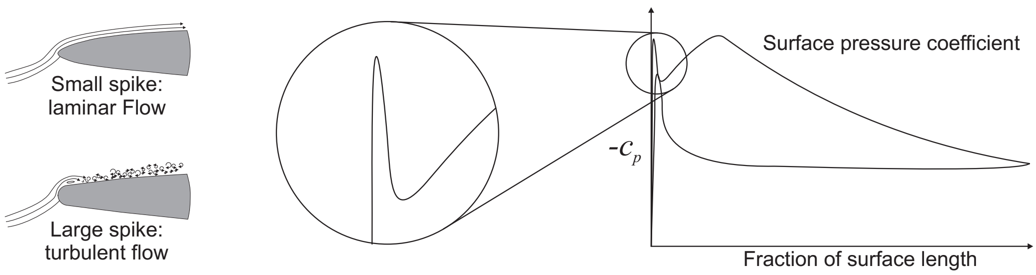

Figure 2: Schematic of surface pressure distribution with enlargement of spike

A freak result was, however, published by Carter (1961). He tested a sharp leading edge and was surprised to find that it operated with low loss over a very wide operating range. To determine the cause of Carters paradoxical result, the ideal leading edge geometry was sought. To achieve this, an optimisation was undertaken; the CFD code utilised was chosen for its ability to predict laminar flow. The optimisation aimed to maximise the blade's incidence range and minimise the loss at the cruise incidence whilst ensuring the leading edge thickness was maintained. A mathematical transform developed by *Boeing* was used to ensure that all aerodynamic geometries could be obtained. The leading edge that turned out to be best started parabolic and merged smoothly onto the aerofoil surface; this was even sharper than Carter's and exhibited no spike over the whole operating incidence range; Carter had inadvertently stumbled across a practical laminar flow leading edge; restrictions in how leading edges are traditionally parameterised had prevented this being discovered before.

The performance of the new, laminar flow, leading edge was investigated over the Reynolds numbers expected within engines. At low engine Reynolds numbers ($Re<0.7 \times 10^5$) where large extents of laminar flow are possible, typical reductions in profile loss of up to 30% were predicted. At the highest cruise Reynolds numbers ($Re \sim 1.2 \times 10^5$), where laminar flow becomes more difficult to obtain, reductions were lower, typically around 10%. In these high Reynolds number cases the majority of the benefit arose from the removal of the leading edge separation bubble. The benefits observed in incidence range were found to be independent of Reynolds number.

To produce and maintain such a leading edge in-service would, however, be prohibitively expensive. Thus if spikes will exist in reality, their consequences must be understood. This raises the question, do small spikes affect blade performance. This was answered by comparing the performance of the new, parabolic leading edge, with no spike, to a 3:1 elliptical leading edge which had a spike that was just small enough to prevent a leading edge separation across the incidence range. The two leading edges were tested on the stators of the low speed compressor; no difference existed in the measured loss indicating that small spikes would be acceptable. This result is, however, surprising given that the transition process differs between the two blades. This transition process is, in reality, periodically unsteady, caused by the wakes of the upstream rotors (which move relative to the stators) promoting premature transition. The process for both blades is shown in a space-time diagram of suction surface intermittency, γ in Figure 3. Intermittency indicates the probability that the flow will be instantaneously turbulent and was calculated from boundary layer hotwire traverses.

The effect of having a small spike at the leading edge was two fold. Firstly wake induced transition occurred closer to the leading edge, this is because the small spike initiated early transition. Secondly, transition between wake interactions was delayed further downstream; this was because of the existence of a strong calmed region of flow. The calmed region trails the wake induced turbulent spots and within it the flow is laminar-like; however, the boundary layer profile is much fuller than that of an unperturbed laminar layer inhibiting both transition and separation. Earlier wake induced transition with the small spike caused a stronger calmed region delaying transition between wakes. The result was the same mean transition location and consequently no change in loss.

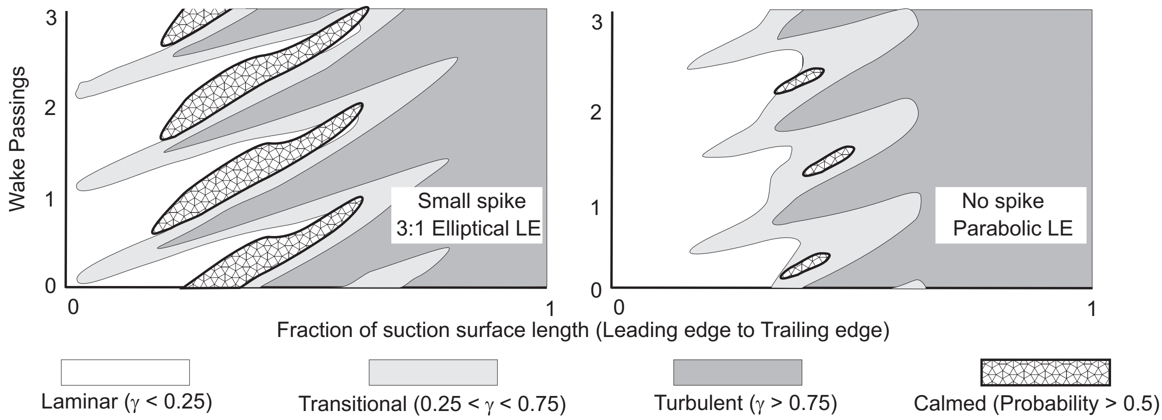

Figure 3: The effect of small spikes on transition: Contours of time-resolved suction surface transition process at design incidence

The insensitivity of leading edges to small spikes meant that a criterion could be formulated. It was found that if the velocity ratio between the trough and the peak of the spike was kept above 0.9 then the boundary layer would remain attached and the benefits of laminar flow leading edges would be obtained. It is clear from the measurement of Rolls Royce blades that this is being regularly achieved on the production line highlighting where their benefits in performance arise. The question that now needs to be answered is how to ensure that in-service blades maintain laminar flow. This work will be carried out during a Research Fellowship sponsored by *St John's College Cambridge* and *Rolls Royce*.

Publications

Goodhand, M.N. and Miller, R.J., 2010, "The impact of real geometries on three-dimensional separations in compressors", *Proceedings of the ASME*, Paper GT2010-22246. **(Best Paper Award)**

Goodhand, M.N., 2010 *Compressor leading edges*, PhD Thesis, Univ. Cambridge, UK

Goodhand, M.N. and Miller, R.J., 2011, "Compressor leading edge spikes: A new performance criterion. *ASME Journal of Turbomachinery,* **133** pg021006

References

Norris, G. J. (2008), "Rolling enhancement: Rolls delivers upgraded Trent 700 to Airbus as three-way A330 market battle intensifies" *Aviation Week*, 8th December 2008 pg. 42.

Carter, A.D.S, 1961, "Blade Profiles for Axial Flow Fans, Pumps and Compressors etc," *Proc. Inst. Mech. Eng*., **175**_15_, pp. 775–806